Tampereen yliopisto

Eetu Takala

# COMPARISON OF WIRELESS COMMUNICATION TECHNOLOGIES FOR MACHINE TYPE COMMUNICATION -APPLICATIONS

Electronics
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# ABSTRACT

Eetu Takala: Comparison of wireless communication technologies for Machine Type Communication -applications
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The rising popularity of wireless communication between devices has created a growing need for communication technologies catering for Machine Type Communication -applications. This popularity has driven the development of multiple different communication technologies with varying features and performance. Since the requirements for wireless communication solutions for different applications tend to vary as well, selecting a proper communication technology plays a key role in overall system performance and efficiency.

The purpose of this thesis is to gather relevant information on the competitive landscape of wireless communication regarding Machine Type Communication and to offer a solution for wireless communication of smart energy meters for Aidon Oy. The goal of this thesis was achieved through reviewing relevant literature of the field.

Based on the research, there are two prominent wireless communication technologies with appropriate features that reasonably cover the requirements of Aidon: Narrowband Internet of Things (NB-IoT) and enhanced Machine Type Communications (eMTC). As the performance of both NB-IoT and eMTC are sufficient, the more cost-efficient option should be selected. A lack of publicly available concrete data makes direct comparison of costs difficult. However, considering the lower device complexity and data rate of NB-IoT, it is reasonable to assume that both module and its operating costs are lower for NB-IoT. Therefore, making NB-IoT the preferable choice.

Keywords: Wireless communication, Machine Type Communication, Internet of Things, eMTC, NB-IoT, EC-GSM-IoT

# TIIVISTELMÄ

Eetu Takala: Laitteiden väliseen langattomaan viestintään tarkoitettujen teknologioiden vertailu
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Laitteiden välisen langattoman viestinnän nouseva suosio on kasvattanut kysyntää laitteiden väliseen kommunikaatioon erikoistuineille teknologioille. Tämä suosio on edistänyt monien eri kommunikaatioteknologien kehitystä, jotka eroavat toisistaan suuresti niin ominaisuuksien, kuin suorituskyvynkin osalta. Koska järjestelmävaatimukset eri kommunikaatioratkaisuille vaihtelevat paljon, oikean teknologian valinta vaikuttaa olennaisesti koko järjestelmän suorituskykyyn ja tehokkuuteen.

Tämän diplomityön tarkoituksena on kerätä tietoa laitteiden väliseen langattomaan viestintään erikoistuineista teknologioista ja esittää langaton kommunikaatioratkaisu Aidon Oy:n älykkäille energiamittareille. Työ suoritettiin kirjallisuusselvityksenä.

Suoritettu tutkimus paljasti kaksi langatonta viestintäteknologiaa, jotka omaavat tarpeelliset ominaisuudet Aidonin vaatimuksiin nähden: Narrowband Internet of Things (NB-IoT) and enhanced Machine Type Communications (eMTC). Molempien teknologioiden suorituskyky on riittävällä tasolla, joten kustannustehokkaampi ratkaisu on paras valinta. Kustannusten vertailua hankaloittaa julkisesti saatavilla olevan datan puute, mutta ottamalla huomioon NB-IoT:n yksinkertaisemman laiterakenteen ja pienemmät datanopeudet, voidaan olettaa NB-IoT:n moduulien hintojen ja käyttökustannuksien olevan pienemmät. Täten osoittaen NB-IoT:n olevan suotavampi valinta.

Avainsanat: Langaton viestintä, laitteiden välinen kommunikaatio, esineiden internet, eMTC, NB-IoT, EC-GSM-IoT

Tämä diplomityö on tarkistettu käyttäen Turnitin OriginalityCheck -palvelua

# PREFACE

This thesis was commissioned by a Nordic company Aidon Oy to research the current technological landscape of wireless communication to find an optimal communication technology for smart energy devices. Originally, the goal was also to include measurements from modules utilizing some of the communication technologies discussed in this thesis. However, due to technical difficulties with the communication modules we received from various sources, this section was eventually omitted to maintain a reasonable time frame regarding the completion of this thesis.

From Aidon, I would like to thank Juha Lohvansuu for providing me with the topic and guidance along the way. I would also like to thank the examiners of this thesis Professor Karri Palovuori and Professor Jukka Vanhala. Finally, I would like to thank my friends and family for supporting me all the way through this process. Writing this thesis has been an excellent learning experience which is sure to aid me in the years to come.

In Tampere, Finland, on 30 December 2019

Eetu Takala

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# LIST OF SYMBOLS AND ABBREVIATIONS

| | |
|---|---|
| ACB | Access Class Barring |
| aka. | Also known as |
| BLE | Bluetooth Low Energy |
| BLER | Block Error Rate |
| BPSK | Binary Phase Shift Keying |
| BT SIG | Bluetooth Special Interest Group |
| CE | Coverage Enhancement |
| CSMA-CA | Carrier-Sense Multiple Access with Collision Avoidance |
| DBPSK | Differential Binary Phase-Shift Keying |
| DL | Downlink |
| DSP | Digital Signal Processor |
| DSSS | Direct-Sequence-Spread-Spectrum |
| EAB | Extended Access Barring |
| EC-AGCH | Extended Coverage Access Grant Channel |
| EC-BCCH | Extended Coverage Broadcast Channel |
| EC-CCCH | Extended Coverage Common Control Channel |
| EC-GSM-IoT | Extended Coverage Global System for Mobile Communications Internet of Things |
| EC-PACCH | Extended Coverage Packet Associated Control Channel |
| EC-PCH | Extended Coverage Paging Channel |
| EC-PDTCH | Extended Coverage Packet Data Traffic Channel |
| EC-RACH | Extended Coverage Random Access Channel |
| EC-SCH | Extended Coverage Synchronization Channel |
| EDGE | Enhanced Data Rates for GSM Evolution |
| eDRX | Extended Discontinuous Reception |
| EGPRS | Enhanced General Packet Radio Service |
| eNB | Evolved Node B |
| ESD | Energy Service Device |
| FCCH | Frequency Correction Channel |
| FDD | Frequency Division Duplex |
| FD-FDD | Full-Duplex Frequency-Division Duplex |
| GFSK | Gaussian Frequency Shift Keying |

| | |
|---|---|
| GMSK | Gaussian Minimum Shift Keying |
| GPRS | General Packet Radio Service |
| eMTC | Enhanced Machine Type Communications |
| HARQ | Hybrid Automatic Repeat Request |
| HD-FDD | Half-Duplex Frequency-Division Duplex |
| HES | Head-End System |
| IoT | Internet of Things |
| LPWAN | Low Power Wide Area Networks |
| LR-WPAN | Low-Rate Wireless Personal Area Network |
| LTE | Long Term Evolution |
| MCD | Multi-Connectivity Device |
| MCL | Maximum Coupling Loss |
| MCS-1 | Modulation and Coding Scheme 1 |
| MIB | Master Information Block |
| MIMO | Multiple Input Multiple Output |
| MPDCCH | MTC Physical Downlink Control Channel |
| MTC | Machine-Type Communication |
| M2M | Machine to Machine |
| NB-IoT | Narrowband Internet of Things |
| NPBCH | Narrowband Broadcast Channel |
| NPDSCH | Narrowband Physical Downlink Shared Channel |
| NPSS | Narrowband Primary Synchronization Signal |
| NPUSCH | Narrowband Physical Uplink Shared Channel |
| NSSS | Narrowband Secondary Synchronization Signal |
| PBCH | Physical Broadcast Channel |
| PDCP | Packet Data Convergence Protocol |
| PDSCH | Physical Downlink Shared Channel |
| PRACH | Physical Random Access Channel |
| PRB | Physical Resource Block |
| PSM | Power Saving Mode |
| PSS/SSS | Primary Synchronization Signal/Secondary Synchronization Signal |
| PUCCH | Physical Uplink Control Channel |
| PUSCH | Physical Uplink Shared Channel |

| | |
|---|---|
| QPSK | Quadrature Phase Shift Keying |
| RFID | Radio Frequency Identification |
| RLC | Radio Link Control |
| RRC | Radio Resource Control |
| SIB1-BR | System Information Block 1 Bandwidth-Reduced |
| SINR | Signal to Interference plus Noise Power Ratio |
| TBCC | Tail-Biting Convolutional Code |
| TBS | Transport Block Size |
| TDD | Time-Division Duplex |
| TDMA | Time Division Multiple Access |
| UE | User Equipment |
| UL | Uplink |
| UNB | Ultra Narrow Band |
| WMN | Wireless Mesh Network |
| 3GPP | 3rd Generation Partnership Project |
| 8PSK | Eight Phase Shift Keying |

# 1. INTRODUCTION

Wireless communication has been a part of human life throughout the ages. From simple hand gestures to talking and smoke signals, wireless communication in its basic form has always been an integral aspect of society. In the modern era, wireless communication has been widely associated with cellular telephony, as it has played central role in long range communication people use on a daily basis. However, with the increase in both variety and numbers of wirelessly communicating devices in recent years, our concept of wireless communication has widened. Nowadays, wireless communication is utilized by a multitude of different applications, such as utility meters, sensors, radio frequency identification (RFID) technology and various household items, with new innovations being introduced as technology advances. [1, p. 4]

As the popularity of wireless communication rises, the demand for reliable communication between devices increases. This form of communication is often classified as machine type communication (MTC). MTC applications for the most part don't have the high throughput requirements of modern person to person communication methods, which creates a market for wireless communication technologies specifically designed for reliable low-throughput communication between devices. [2, p. 3 – 4]

Multiple communication technologies have been developed to meet the rising demand for MTC. Cellular communication technologies operating in the licensed frequency spectrum such as eMTC, NB-IoT and EC-GSM-IoT developed by 3rd Generation Partnership Project (3GPP) were released in 2016 and they have since gained popularity on a global scale [2, p. 2] [3]. Additionally, multiple technologies operating in the unlicensed frequency spectrum such as IEEE 802.15.4, Wi-Fi HaLow, Bluetooth Low Energy, wireless mesh networks, LoRa and Sigfox have been released as well. All these technologies cater towards machine type communication, giving companies invested in MTC -applications a vast array of technologies to choose from. However, these technologies have major differences when it comes to performance, reliability, infrastructure required, cost and availability, which makes it important to choose a technology that best suits the task at hand. [2, p. 8 – 12] [4]

This thesis is done for Aidon Oy, a Finnish company providing smart energy meters and related services in the Scandinavian area. The purpose of this thesis is to investigate and compare prominent wireless communication technologies for MTC -applications with the objective of finding an optimal communication solution for the metering network of Aidon. The goal of this thesis is achieved through reviewing the relevant literature of the field.

Chapter 2 of this thesis provides an overview of the technological landscape of MTC by presenting the prevailing wireless communication technologies catering towards MTC -applications. Chapter 3 compares the performance of relevant MTC technologies and investigates the differences between licensed and unlicensed technologies. Chapter 4 Provides an overview of Aidon Oy and its requirements for a new communication technology.

# 2. TECHNOLOGIES FOR WIRELESS COMMUNICATION

In this chapter the prevailing wireless communication technologies for Machine Type Communication (MTC) purposes are presented with a focus on three cellular Internet of Things (IoT) technologies: enhanced Machine Type Communication (eMTC), Narrow-Band Internet of Things (NB-IoT) and Extended Coverage Global System for Mobile Communications Internet of Things (EC-GSM-IoT). Specified in the 3rd Generation Partnership Project (3GPP) release 13 in 2016, the three aforementioned technologies have been developed to meet the growing demand for MTC communication and despite being recently released, they have quickly gained traction on a global scale [2, p. 2] [3].

In addition to eMTC, NB-IoT and EC-GSM-IoT that operate in the licensed spectrum, this chapter also discusses technologies operating in the unlicensed spectrum, including IEEE 802.15.4, Wi-Fi HaLow, Bluetooth Low Energy, wireless mesh networks, LoRa and Sigfox [2, p. 1].

## 2.1 eMTC

### 2.1.1 Background

Enhanced Machine Type Communications (eMTC), also referred to as Long Term Evolution (LTE) Cat-M1, is a low power wide area technology specified in 3rd Generation Partnership Project (3GPP) release 13 in 2016. With many improvements over its predecessor LTE Cat-0 introduced in release 12, eMTC aims to provide reliable and efficient communication for mid-range to low-end Internet of Things (IoT) applications. [3] [5, s. 137] [6] [7]

Due to the increasing popularity of communication between devices, 3GPP decided to launch a study on provision of low-cost Machine-Type Communications (MTC) User Equipments (UEs) based on LTE. The study gave rise to low cost and enhanced coverage MTC UE for LTE in 3GPP release 12 completed in 2015, which introduced LTE device Cat-0. This new UE device category came with reduced data-rate, modified half duplex operation, possibility for devices to have only one receive antenna and a power-saving mode. Further enhancements for MTC were made in 3GPP release 13 which was completed in 2016. It introduced a new low power wide area technology eMTC, which was designed with the following objectives: [3] [5, s. 137 – 139] [8]

- Low device complexity and cost
- Coverage enhancement
- Long device battery lifetime
- Support for massive number of devices
- Deployment flexibility

Low device cost through low complexity is an important factor in making LTE appealing for low-end MTC applications. Major improvements on this front were already made during development of Cat-0 in release 12 by reducing the peak rate to 1 Mbit/s for both downlink (DL) and uplink (UL), having only one receive antenna and having half-duplex frequency-division duplex (HD-FDD) operation as an option. EMTC supports all these improvements made in release 12 and also employs further cost reduction techniques. More specifically eMTC has a reduced bandwidth of 1.4 MHz (instead of 20MHz) and a reduced maximum transmit power of 20 dBm (instead of 23 dBm). With all these cost reduction techniques combined, the cost of an eMTC modem was estimated to be on par with an enhanced GPRS (EGPRS) modem. [5, s. 137 – 138] [8]

The goal for coverage enhancement (CE) in eMTC was to enable proper device operation with at least 15 dB higher coupling loss compared to previous LTE devices. On top of the required coverage increase of 15 dB, the coverage enhancement techniques used would also have to compensate for the use of lower transmit power and single receive antenna in eMTC devices. Since eMTC has quite relaxed requirements on data rates and latency, 3GPP decided that the best way to increase coverage was through repetition or retransmission techniques, thus trading off data rate for coverage. For this purpose, 3GPP standardized two CE modes: CE mode A, targeting modest coverage enhancement by supporting up to 32 subframe repetitions, and CE mode B, targeting more extensive coverage enhancement by supporting up to 2048 subframe repetitions. Devices will be assigned appropriate CE modes individually by the network to ensure proper coverage. [5, s. 138] [8]

Long device battery lifetime in LTE MTC devices is mainly achieved through lower power consumption. Compared to regular LTE devices, LTE MTC devices can already have lower power consumption while active due to reduced receive and transmit bandwidths. To further increase the battery lifetime for LTE MTC devices, release 12 introduced a power saving mode (PSM). [5, s. 138] [8] PSM increases the time the device spends in sleep mode thus making it unreachable by paging. It's similar to unpowered state, but the device remains registered to the network, which means after the device wakes up there is no need to re-establish necessary connections. Because the device is not reachable during PSM, it is mainly intended to be used by latency tolerant applications. Release 13 introduced extended discontinuous reception (eDRX) which further decreases power consumption by going into sleep mode and only waking up at pre-determined timeslots to check for DL data by decoding the Physical Downlink Control Channel (PDCCH). PSM and eDRX are meant for LTE MTC devices in general and they are used by both eMTC and NB-IoT. [6] [9] The function of PSM and eDRX is illustrated in figure 1. [10]

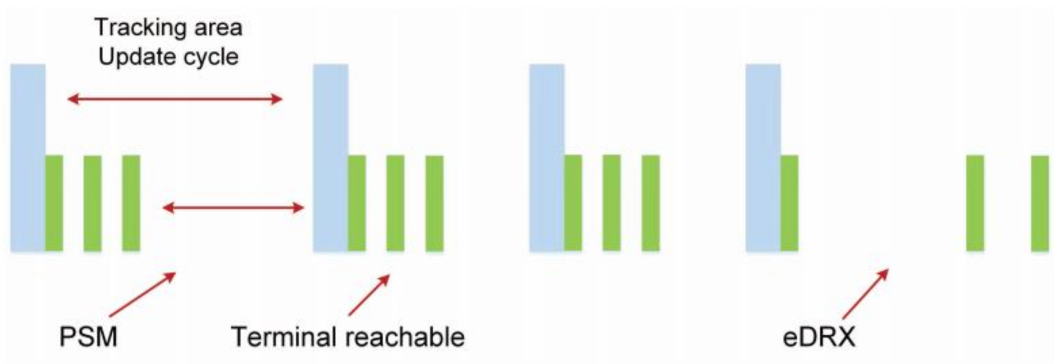


***Figure 1.*** *PSM and eDRX functionality [10].*

Even before release 13, some advancements have been made to support a massive number of devices in LTE networks. For example, Access Class Barring (ACB) and Extended Access Barring (EAB), introduced for LTE in releases 8 and 11, alleviate the traffic that could occur when multiple devices attempt to access the network simultaneously, thus providing protection from congestion for the radio access and core network. In addition to these previous advancements, eMTC also supports Radio Resource Control (RRC) suspend/resume mechanism specified in release 13. This mechanism helps reduce the signaling necessary to resume an RRC connection after the device has been idle. [5, s. 17 – 21, 139]

Deployment flexibility of eMTC stems from its compatibility with existing LTE networks and spectrum. EMTC only supports in band deployment; however, an eMTC device can be deployed in any LTE evolved Node B (eNB) configured to support eMTC without affecting the service of other LTE devices by the same eNB. This means that eMTC can be deployed to existing LTE networks via a software upgrade. [9] [11]

### 2.1.2 Performance

The coverage target for eMTC was set to 155.7 dB Maximum Coupling Loss (MCL) assuming the device power class to be 20 dBm with noise figures of 5 dB in the base station and 9 dB in the device. The coverage target for eMTC can be reached and even surpassed because of the sufficient support of repetitions of the physical channels in both DL and UL. According to the evaluations made in reference [5], eMTC can almost reach the coverage target set for Narrowband Internet of Things (NB-IoT) and Extended Coverage Global System for Mobile Communications Internet of Things (EC-GSM-IoT), meaning 164 dB MCL assuming a 3 dB noise figure in the base station and 5 dB in the device. If the device power class is changed to 23 dBm, the coverage of eMTC should only differ from the coverage target of NB-IoT and EC-GSM-IoT by a margin of 4.3 dB in the DL and 3.3 dB in the UL. The coverage evaluations of different eMTC physical channels with HD-FDD operation are shown in table 1. To make the coverage results more comparable to NB-IoT and EC-GSM-IoT, multiple assumptions were made as can be seen from table 2. [5, s. 200 – 202]

***Table 1.*** *eMTC coverage evaluations [5, p. 201]*

| # | Physical channel name | PUCCH | PRACH | PUSCH | PDSCH | MPDCCH | PBCH, MIB | PDSCH, SIB1-BR | PSS/SSS |
|---|---|---|---|---|---|---|---|---|---|
| 1 | BLER target [%] | 10 % | 10 % | 10 % | 6 % | 10 % | 90th perc. | 90th perc. | 90th perc. |
| 2 | TBS [bits] | – | – | 392 | 936 | – | – | 152 | – |
| 3 | Repetitions | 32 | 128 | 2048 | 1024 | 64 | – | 16 | |
| 4 | Data rate [bps], acquisition time [ms] | – | – | 167 bps | 0.8 kbps | – | 640 ms | 640 ms | 460 ms |
| **Transmitter** | | | | | | | | | |
| 5 | Total Tx power [dBm] | 23 | 23 | 23 | 46 | 46 | 46 | 46 | 46 |
| 6 | Power boosting [dB] | – | – | – | – | – | 3 | – | 3 |
| 7 | Actual Tx power [dBm] | 23 | 23 | 23 | 36.8 | 36.8 | 39.8 | 36.8 | 39.8 |
| **Receiver** | | | | | | | | | |
| 8 | Thermal noise [dBm/Hz] | –174 | –174 | –174 | –174 | –174 | –174 | –174 | –174 |
| 9 | Receiver noise figure [dB] | 3 | 3 | 3 | 5 | 5 | 5 | 5 | 5 |
| 10 | Interference margin [dB] | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 11 | Channel bandwidth [kHz] | 180 | 1080 | 180 | 1080 | 1080 | 1080 | 1080 | 1080 |
| 12 | Effective noise power [dBm] = (8) + (9) + (10) + 10 $\log_{10}$ (11) | –118.5 | –110.7 | –118.5 | –108.7 | –108.7 | –108.7 | –108.7 | –108.7 |
| 13 | Required SINR (dB) | –24 | –31.2 | –23.6 | –18.5 | –18.5 | –15.5 | –18.5 | –16.2 |
| 14 | Dual antenna receiver sensitivity [dBm] = (12) + (13) | –142.5 | –141.9 | –142.1 | –127.2 | –127.2 | –124.2 | –123.7 | –124.9 |
| 15 | MCL [dB] = (7) - (14) | 165.5 | 164.9 | 165.1 | 164 | 164 | 164 | 164 | 164.7 |

***Table 2.** eMTC coverage evaluation assumtions [5, p. 202].*

| Parameter | Value |
|---|---|
| Frequency band | 2 GHz |
| Propagation condition | PUCCH, PRACH, PUSCH, PBCH, PSS/SSS: ETU<br>PDSCH, MPDCCH: EPA |
| Fading | Rayleigh, 1 Hz |
| Frequency error | PSS/SSS: 1 kHz<br>PDSCH, MPDCCH, PUCCH, PRACH, PUSCH: 25 or 30 Hz<br>PBCH, PDSCH SIB1-BR: 50 Hz |
| Device NF | 5 dB |
| Device antenna configuration | One transmit antenna and one receive antenna |
| Device power class | 23 dBm |
| Base station NF | 3 dB |
| Base station antenna configuration | Two transmit antennas and two receive antennas |
| Base station power level | PSS, SSS, PBCH: 39.8 dBm per narrowband<br>MPDCCH, PDSCH: 36.8 dBm per narrowband |
| Frequency hopping (FH) | PSS, SSS, PBCH: N/A<br>MPDCCH, PDSCH, PUSCH, PUCCH, PRACH: FH enabled |
| Resource allocation | PSS, SSS, PBCH: N/A<br>PDSCH, MPDCCH: 6 PRBs<br>PUSCH, PUCCH: 1 PRB<br>PRACH: 6 PRBs |

With the added evaluation assumptions mentioned in table 2, the coverage of eMTC reaches 164 dB MCL on all physical channels thus meeting coverage target of NB-IoT and EC-GSM-IoT. The LTE physical channels listed in table 1 are Physical Uplink Control Channel (PUCCH), Physical Random Access Channel (PRACH), Physical Uplink Shared Channel (PUSCH), Physical Downlink Shared Channel (PDSCH), MTC Physical Downlink Control Channel (MPDCCH), Physical Broadcast Channel (PBCH) with Master Information Block (MIB), PDSCH with System Information Block 1 Bandwidth-Reduced (SIB1-BR) and Primary Synchronization Signal/Secondary Synchronization Signal (PSS/SSS). Table 1 also lists the Block Error Rate (BLER), Transport Block Size (TBS) and the required Signal-to-Interference-plus-Noise Power Ratio (SINR) used in the evaluations. [5, p. 200 – 202]

Data rates for eMTC DL and UL in HD-FDD operation are shown in table 3. The instantaneous peak data rate of 1 Mbps can be achieved when a 1000-bit transport block is transmitted during subframes. When taking into consideration delays related to the transmission over a longer period of time a peak physical layer throughput of 300 kbps can be reached for the DL and 375 kbps for the UL. Data rates are further reduced when taking into account high coupling losses. [5, p. 203 – 205]

***Table 3.*** *eMTC DL and UL data rate [5, p. 204 – 205].*

| | 164 dB MCL | 154 dB CL | 144 dB CL | Peak | Instantaneous Peak |
|---|---|---|---|---|---|
| Downlink | 0.8 kbps | 9.9 kbps | 76.6 kbps | 300 kbps | 1 Mbps |
| Uplink | 167 bps | 3.1 kbps | 40.1 kbps | 375 kbps | 1 Mbps |

Latency of eMTC is presented in table 4 according to simulations made in reference [5]. The latency is optimized by using RRC resume procedure to establish connection. Table 4 shows that a latency on 0.2 s can be reached with a coupling loss of 144 dB however it climbs to 8.5 s with the MCL of 164 dB. A major reason for high latency at 164 dB coupling loss is the limited data rate of the PUSCH transmission at extreme coverage situations. [5, p. 205 – 207]

***Table 4.*** *eMTC latency [5, p. 207].*

| Coupling Loss [dB] | Latency [s] |
|---|---|
| 144 | 0.2 |
| 154 | 0.6 |
| 164 | 8.5 |

Battery life evaluations for eMTC are presented in table 5. For these evaluations an ideal 5-Wh battery power source is assumed, meaning imperfections such as power leakage are not taken into consideration. Power consumption levels used for the evaluation can be seen in table 6. With lower coupling loss levels eMTC device battery life can reach 36.5 years assuming a 24 h reporting interval. However, when coupling loss increases, the battery life decreases drastically. [5, p. 207 – 209]

***Table 5.*** *eMTC battery life [5, p. 209].*

| Reporting Interval [Hours] | DL Packet Size [Bytes] | UL Packet Size [Bytes] | Battery Life [Years] | | |
|---|---|---|---|---|---|
| | | | 144 dB CL | 154 dB CL | 164 dB CL |
| 2 | 65 | 50 | 23.7 | 13.9 | 2 |
| | | 200 | 22.3 | 8.7 | 0.9 |
| 24 | | 50 | 36.5 | 33.4 | 15.5 |
| | | 200 | 36.2 | 29.9 | 8.8 |

***Table 6.*** *Power consumption values [5, p. 207].*

| Tx, 23 dBm | Rx | Light Sleep | Deep Sleep |
|---|---|---|---|
| 500 mW | 80 mW | 3 mW | 0.015 mW |

Capacity requirements for eMTC were assumed by 3GPP to be 60,680 devices/km$^2$ and 52,547 devices/cell. This assumption was made based on the population density of central London with the assumption of 40 devices per home. Those requirements are easily met according to simulations performed in reference [5]. Assumptions made in the simulations are listed in table 7. Additionally, it was assumed that the LTE downlink narrowbands were outside of the center subcarriers, meaning that the load from PSS, SSS and PBCH transmissions in the downlink were not carried in the narrowbands. In a similar fashion, it was assumed that PRACH transmissions did not contribute to the load carried by the LTE uplink narrowbands. The simulation results are presented in table 8 and they show that eMTC can reach an arrival rate of 40.3 access attempts/s while having a 1% chance of devices not being served by the system. This access rate corresponds to a connection density of 361,000 devices/km$^2$. [5, p. 209 – 211]

***Table 7.*** *Assumptions for eMTC capacity simulation [5, p. 210].*

| **Parameter** | **Model** |
|---|---|
| Cell structure | Hexagonal grid with 3 sectors per size |
| Cell intersite distance | 1732 m |
| Frequency band | 900 MHz |
| LTE system bandwidth | 10 MHz |
| Frequency reuse | 1 |
| Base station transmit power | 46 dBm |
| Power boosting | 0 dB |
| Base station antenna gain | 18 dBi |
| Device transmit power | 23 dBm |
| Device antenna gain | – 4 dBi |
| Device mobility | 0 km/h |
| Path loss model | $120.9 + 37.6 \times \log_{10}(d)$, with d being the base station to device distance in km |
| Shadow fading standard deviation | 8 dB |
| Shadow fading correlation distance | 110 m |

***Table 8.*** *eMTC capacity per narrowband [5, p. 211].*

| **Connection Density at 1% Outage** | **Arrival Rate at 1% Outage** |
|---|---|
| 361,000 devices/km$^2$ | 40.3 access attempt/s |

A reduced device cost through low complexity compared to previous LTE device categories was an integral part of eMTC development. Even with multiple concessions, eMTC doesn’t quite reach the ultralow complexity levels of NB-IoT and EC-GSM-IoT devices. However, since eMTC aims to facilitate a larger range of use cases supporting higher throughput applications, higher device complexity is required. The key features of eMTC regarding device complexity are presented in table 9. [5, p. 213].

***Table 9.*** *Overview of eMTC device complexity [5, p. 213].*

| Parameter | Value |
|---|---|
| Duplex modes | HD-FDD, FD-FDD, TDD |
| Half-duplex operation | Type B |
| Number of receive antennas | 1 |
| Transmit power class | 20, 23 dBm |
| Maximum DL/UL bandwidth | 6 PRB (1.080 MHz) |
| Highest DL/UL modulation order | 16QAM |
| Maximum number of supported DL/UL spatial layers | 1 |
| Maximum DL/UL TBS | 1000 bits |
| Peak DL/UL physical layer data rate | 1 Mbps |
| DL/UL channel coding type | Turbo code |
| DL physical layer memory requirement | 25,344 soft channel bits |
| Layer 2 memory requirement | 20,000 bytes |

3GPP concluded that if eMTC modem price is to be on par with that of an EGPRS modem, the modem price should be reduced to about 1/3 of the price of a previously cheapest LTE alternative, a single-band LTE Cat-1 device. With all the design parameters listed in table 9, eMTC modem has the potential to reach prices even lower than the aforementioned level. [5, p. 213].

## 2.2 NB-IoT

### 2.2.1 Background

Narrowband Internet of Things (NB-IoT) is a narrowband communication system originating from 3$^{rd}$ Generation Partnership Project (3GPP) release 13 in 2016. NB-IoT was created to answer the growing demand for Machine to Machine (M2M) communication, specifically low-cost, low-power and wide-area cellular connectivity for IoT applications. [12]

For a long time, GSM/GPRS was the most popular cellular technology largely due to its maturity as a technology and its low modem cost. However, when new low power wide area networks (LPWAN) technologies started to emerge, 3GPP began conducting a feasibility study on cellular system support for ultra-low complexity and low throughput internet of things. The study was set up with demanding objectives regarding coverage, capacity and battery lifetime.

Although the goal for maximum system latency in the study was set relatively low, the end result would provide major improvements over GSM/GPRS. In addition to performance requirements, the study also aimed to make the introduction of IoT features to existing GSM networks possible via a software upgrade. Since setting up a national network requires a great deal of time, effort and resources, being able to upgrade pre-existing infrastructure overnight with a software update would ease the introduction of IoT features tremendously. [5, s. 219]

Although there were a few solutions proposed to the study that were backwards compatible with the existing GSM network (e.g. EC-GSM-IoT), certain GSM operators had been considering refarming their existing GSM spectrum to Long-Term Evolution (LTE) and LPWAN focused on IoT applications. Because of this shift in interests, 3GPP also started studying technologies that were not backwards compatible with GSM. Even though this new direction in the study didn’t produce any specific technologies, it laid the groundwork for NB-IoT that would be later standardized in 3GPP Release 13. [5, s. 219 – 220]

The core specifications of NB-IoT were developed in only a few short months and were finished in June 2016.  The fast development cycle was aided by utilizing many technical components that were already in use for LTE, thus placing NB-IoT as a part of 3GPP LTE specifications. Using multiple components from LTE proved to be majorly beneficial in other ways as well since it reduced the standardization process and provided a possibility to introduce NB-IoT to existing LTE networks via a software upgrade. These aspects reduced the time-to-market and made it easier to start using the technology, which was all the more promising for NB-IoT as within a year of its completion multiple networks and devices began to appear. [5, s. 220]

NB-IoT was developed in accordance with a multitude of objectives set in 3GPP Release 13 that include: [5, s. 220] [12]

- Extremely low device complexity enabling a low module cost.
- Substantial coverage enhancements over GPRS.
- Support of massive number of low-throughput devices.
- Improved battery life.
- Deployment flexibility.

Low module cost through a very low device complexity is made possible by making multiple concessions regarding the technology and its components. NB-IoT system only requires a bandwidth of 180 kHz to function. NB-IoT only supports half-duplex operation which means downlink cannot be listened to simultaneously while transmitting in the uplink and vice versa. Only one receiver antenna is used thus preventing the use of multiple input multiple output (MIMO) transmissions. Processing time is relaxed, and peak data rates are reduced by restricting the maximum transport block size (TBS) to 680 bits for the downlink and to 1000 bits for the uplink. Instead of using the more demanding LTE turbo code, NB-IoT utilizes a simpler convolutional code i.e. the LTE tail-biting convolution code. Regarding modulation, downlink utilizes quadrature phase shift keying (QPSK) while uplink uses single tone transmissions with π/2-binary phase shift keying (BPSK) and π/4-QPSK to reduce peak-to-average power ratio. NB-IoT also supports only one hybrid automatic repeat request (HARQ) process for both downlink and uplink. [5, s. 220 – 221] [12] [13]

The coverage of NB-IoT is enhanced through repetitions, giving devices even in challenging locations a way to reliably communicate, albeit at a reduced data rate. By sacrificing data rate in favor of coverage, NB-IoT manages to enhance its coverage by 20 dB in all operation modes over GPRS. In addition, NB-IoT uses an almost constant envelope waveform in the uplink which increases coverage for hard to reach devices by minimizing the need to back off the output power from the maximum configurable level. [5, s. 221] [13]

The ability for NB-IoT to support a massive number of low-throughput devices is mainly attributed to the use of narrow subcarriers, which is important for the uplink as it allows multiple devices to transmit simultaneously. NB-IoT also separates devices into specific coverage classes and distributes resources accordingly. This means that devices in hard to reach places operate with lower data rates and higher latency than those in areas with good coverage. Even with this resource allocation, devices in poor coverage areas are still able to communicate with the throughput and latency requirements set for NB-IoT. The use of this type of resource allocation optimizes overall system capacity. [14, s. 317]

Deployment flexibility of NB-IoT stems from its three modes of operation: in-band, guard-band and stand-alone. In-band mode allows deployment directly within

LTE frequency band, using one of the LTE physical resource blocks (PRBs). With guard-band mode, deployment is possible by utilizing the LTE guard band. In-band and guard-band modes of operation are illustrated in figure 2. Stand-alone mode of operation allows the deployment of NB-IoT as a stand-alone carrier. For this type of deployment any available frequency spectrum can be used as long as the bandwidth remains larger than 180 kHz. Although, 100 kHz guard bands are recommended to be used if NB-IoT is deployed in refarmed GSM spectrum due to NB-IoT needing to meet the GSM spectral mask which is specified according to 200 kHz channelization. Stand-alone mode of operation is illustrated in figure 3. [5, s. 222 – 223]

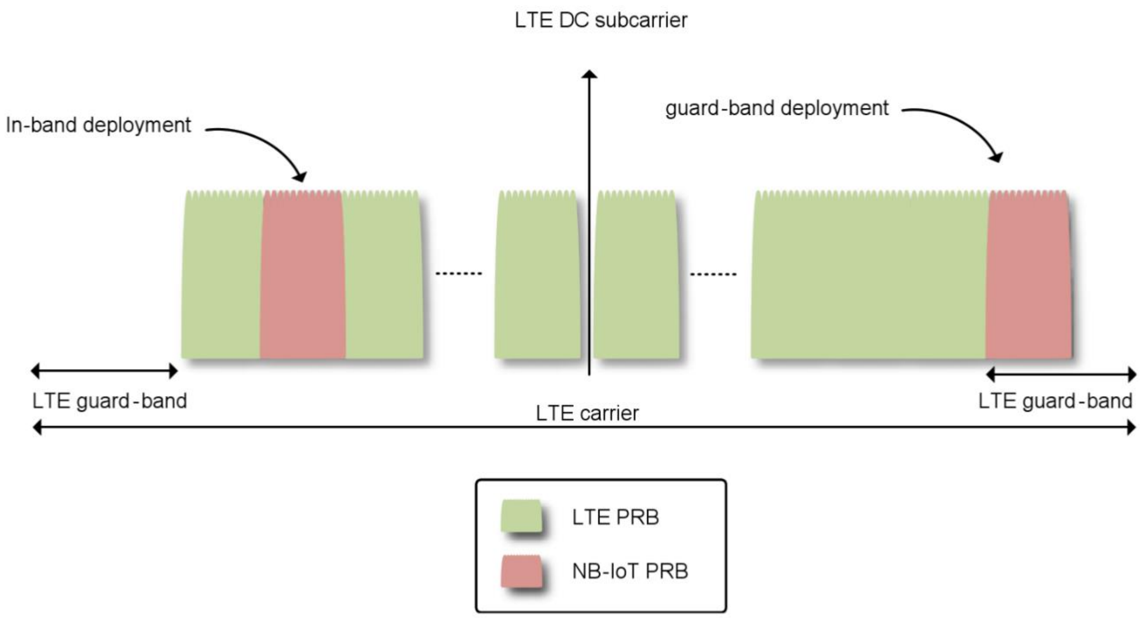


***Figure 2.*** *NB-IoT modes of operation (In-band and guard-band) [5, p. 224].*

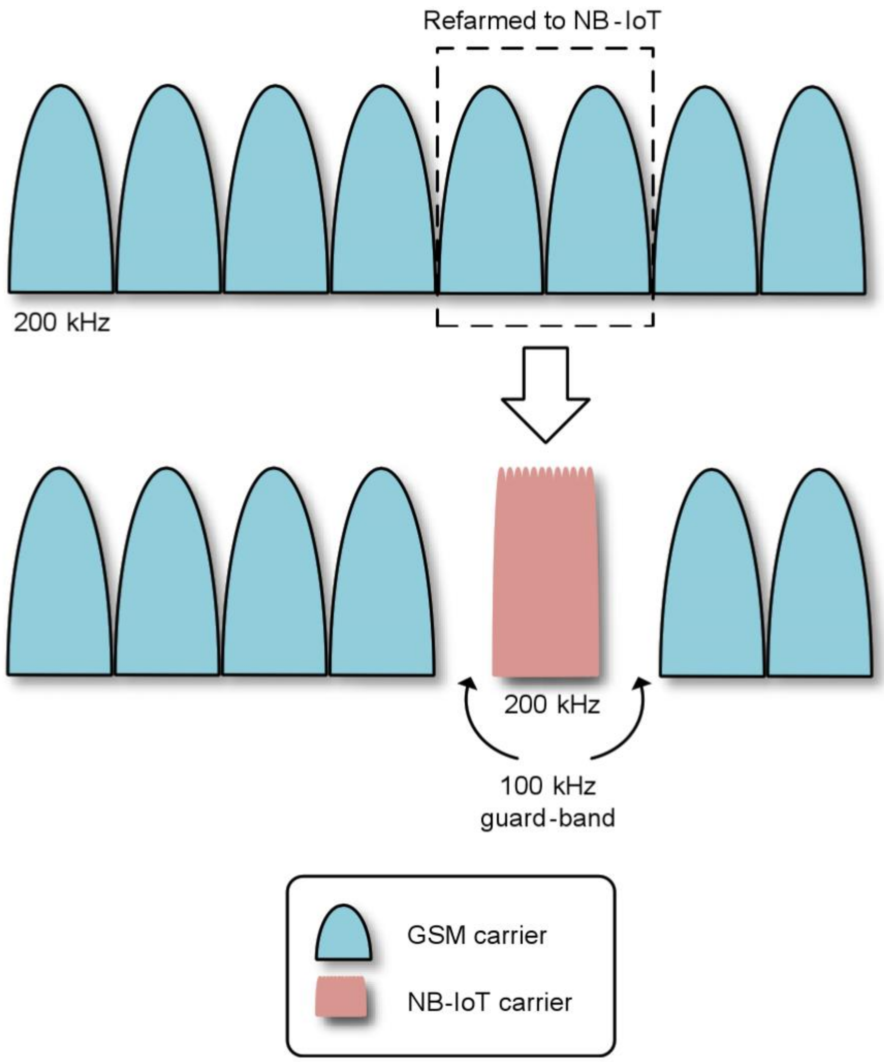


***Figure 3.*** *NB-IoT mode of operation (stand-alone) [5, p. 223].*

The vast majority of a NB-IoT device's life cycle is spent on idle mode. For this reason, improving the battery life for NB-IoT devices is mainly achieved through lowering power consumption while the device does not have an active data session. To save power in this fashion NB-IoT uses power saving mode (PSM) and expanded discontinuous reception (eDRX). PSM saves power by increasing the time the device spends in deep sleep, meaning that the during this time the device is not reachable by signaling while still being registered online. eDRX further extends this sleep cycle while also reducing power consumption caused by unnecessary startup of receiving cell. The power saving functionality of PSM and eDRX is illustrated in figure 1. [10] In short, to save power PSM and eDRX allow for the device to shut down its transceiver and only maintain basic functionality to keep track of time, so the device knows when to start up its transceiver again [5, s. 221].

### 2.2.2 Performance

The design objectives set during the 3GPP study on Cellular System Support for Ultra-Low Complexity and Low Throughput Internet of Things apply for both EC-GSM-IoT and NB-IoT and they include: [5, p. 106]

- Maximum Coupling Loss (MCL) of 164 dB
- Minimum data rate of 160 bps
- Service latency of 10 seconds
- Device battery life of up to 10 years
- System capacity of 60,000 devices/km$^2$
- Ultra-low device complexity

In addition, NB-IoT aims for deployment flexibility with three different deployment modes: in-band, guard-band and stand-alone. For NB-IoT to achieve MCL of 164 dB on all its deployment modes in DL, its physical channels must have sufficient performance at the coverage level of 164 dB with Signal-to-Interference-plus-Noise power ratio (SINR) of -4.6 dB for stand-alone operation and -12.6 dB for in-band and guard-band operation as described in the NB-IoT DL link budget in table 10. The link budget is based on the NB-IoT parameter assumptions agreed by 3GPP. The parameter assumptions are shown in table 11. [5, p. 300 – 302]

***Table 10.*** *NB-IoT DL link budget [5, p. 302].*

| # | Operation Mode | Stand-alone | In-band | Guard-band |
|---|---|---|---|---|
| 1 | Total base station Tx power [dBm] | 43 | 46 | 46 |
| 2 | base station Tx power per NB-IoT carrier [dBm] | 43 | 35 | 35 |
| 3 | Thermal noise [dBm/Hz] | –174 | –174 | –174 |
| 4 | Receiver NF [dB] | 5 | 5 | 5 |
| 5 | Interference margin [dB] | 0 | 0 | 0 |
| 6 | Channel bandwidth [kHz] | 180 | 180 | 180 |
| 7 | Effective noise power [dBm] = (3) + (4) + (5) + 10 $\log_{10}(6)$ | –116.4 | –116.4 | –116.4 |
| 8 | Required DL SINR [dB] | –4.6 | –12.6 | –12.6 |
| 9 | Receiver sensitivity [dBm] = (7) + (8) | –121.0 | –129.0 | –129.0 |
| 10 | Receiver processing gain | 0 | 0 | 0 |
| 11 | Coupling loss [dB] = (2) - (9) + (10) | 164.0 | 164.0 | 164.0 |

***Table 11.*** *NB-IoT radio related parameter assumptions [5, s. 301].*

| Parameter | Value |
|---|---|
| Frequency band | 900 MHz |
| Propagation condition | Typical Urban |
| Fading | Rayleigh, 1 Hz Doppler spread |
| Device initial oscillator inaccuracy | 20 ppm (applied to initial cell selection) |
| Raster offset | Stand-alone: 0 Hz;<br>in-band and guard-band: 7.5 kHz |
| Device frequency drift | 22.5 Hz/s |
| Device NF | 5 dB |
| Device antenna configuration | One transmit antenna and one receive antenna |
| Device power class | 23 dBm |
| Base station NF | 3 dB |
| Base station antenna configuration | Stand-alone: one transmit antenna and two receive antennas |
| | In-band and guard-band: two transmit antennas and two receive antennas |
| Base station power level | 43 dBm (stand-alone), 35 dBm (in-band and guard-band) per 180 kHz |
| Number of NPDCCH/NPDSCH REs per subframe | Stand-alone 160; in-band: 104; guard-band: 152 |
| Valid NB-IoT subframes | All subframes not carrying NPBCH, NPSS, and NSSS are assumed valid subframes |

Adequate performance for NB-IoT physical channels entail that synchronization signals, Narrowband Primary Synchronization Signal (NPSS) and Narrowband Secondary Synchronization Signal (NSSS), need to be detected with a 90% detection rate. In addition, the Master Information Block (MIB) carried by Narrowband Broadcast Channel (NPBCH) needs to support 10% Block Error Rate (BLER) meaning a detection rate of 90%. A minimum data rate of 160 bps for Narrowband Physical Downlink Shared Channel (NPDSCH) must also be achieved. According to the simulations performed in reference [5], including the NPDSCH data rates presented in table 12 show that adequate performance for DL physical channels is achieved and thus the coverage target of 164 dB MCL can be reached for DL. Table 12 shows that a minimum data rate of 160 bps can be reached as simulated results showed data rates ranging from 0.31 kbps to 1.0 kbps for all deployment modes. [5, p. 299 – 307]

***Table 12.*** *NPDSCH performance for stand-alone, in-band and guard-band operation [5, p. 307].*

| Deployment mode | Stand-alone | | | In-band | | | Guard-band | | |
|---|---|---|---|---|---|---|---|---|---|
| Coupling Loss | 144 dB | 154 dB | 164 dB | 144 dB | 154 dB | 164 dB | 144 dB | 154 dB | 164 dB |
| TBS [bits] | 680 | 680 | 680 | 680 | 680 | 680 | 680 | 680 | 680 |
| Number of subframes per repetition | 4 | 6 | 6 | 10 | 8 | 8 | 8 | 5 | 6 |
| Number of repetitions | 1 | 4 | 32 | 1 | 16 | 128 | 1 | 16 | 128 |
| Number of subframes used for NPDSCH transmission | 4 | 24 | 192 | 10 | 128 | 1024 | 8 | 80 | 768 |
| Total TTI required | 4 ms | 32 ms | 272 ms | 12 ms | 182 ms | 1462 ms | 9 ms | 112 ms | 1096 ms |
| Data rate measured over NPDSCH TTI | 170 kbps | 21.3 kbps | 2.5 kbps | 56.7 kbps | 3.7 kbps | 0.47 kbps | 75.6 kbps | 6.1 kbps | 0.62 kbps |
| Physical layer data rate (accounting for scheduling cycle) | 19.1 kbps | 8.7 kbps | 1.0 kbps | 15.3 kbps | 2.4 kbps | 0.31 kbps | 15.3 kbps | 3.8 kbps | 0.37 kbps |

The same requirements apply to NB-IoT UL coverage as well. In similar fashion to DL, simulation results including data rates for Narrowband Physical Uplink Shared Channel (NPUSCH) presented in table 13 show adequate performance for UL physical channels meaning that 164 dB MCL can be reached for UL. In table 13 the data rates for NPUSCH range from 320 bps to 343 bps reaching over the required 160 bps. [5, p. 299 – 311]

***Table 13.*** *NPUSCH performance [5, p. 311].*

| Coupling Loss | 144 dB | 154 dB | 164 dB |
|---|---|---|---|
| TBS [bits] | 1000 | 1000 | 1000 |
| Subcarrier spacing [kHz] | 15 | 15 | 15 |
| Number of tones | 3 | 1 | 1 |
| Number of resource units per repetition | 8 | 10 | 10 |
| Number of repetitions | 1 | 4 | 32 |
| Total TTI required [ms] | 32 | 320 | 2560 |
| Data rate measured over NPUSCH Format 1 TTI | 28.1 kbps | 2.8 kbps | 371 bps |
| Physical layer data rate, stand-alone | 18.8 kbps | 2.6 kbps | 343 bps |
| Physical layer data rate, in-band | 18.7 kbps | 2.4 kbps | 320 bps |
| Physical layer data rate, guard-band | 18.7 kbps | 2.5 kbps | 320 bps |

Peak physical layer data rates for NB-IoT are listed in tables 14 and 15. Table 14 lists the instantaneous peak data rates that are determined purely from the physical channel configurations. For instance, TBS for NPDSCH in release 13 is 680 bits which can be mapped to 3 subframes i.e. 3 ms in the guard-band and stand-alone modes of operation resulting in a peak DL data rate of 226.7 kbps. It should be noted that instantaneous peak data rates do not account for delays resulting from protocol aspects and therefore do not represent the overall channel throughput. However, instantaneous peak data rates can be used to compare the performance of different technologies. [5, p. 312]

***Table 14.*** *NB-IoT instantaneous peak data rate [5, p. 313].*

| | Stand-alone [kbps] | In-band [kbps] | Guard-band [kbps] |
|---|---|---|---|
| NPDSCH | 226.7 | 170.0 | 226.7 |
| NPUSCH multi-tone | 250.0 | 250.0 | 250.0 |
| NPUSCH single-tone (15 kHz) | 21.8 | 21.8 | 21.8 |
| NPUSCH single-tone (3.75 kHz) | 5.5 | 5.5 | 5.5 |

Table 15 shows the peak data rates when accounting for scheduling delays and timing restrictions, giving a clearer picture of the channel throughput over time.

When comparing tables 14 and 15, the data rates for DL and UL multi-tone are drastically decreased in table 15. DL data rate of 226.7 kbps for stand-alone and guard-band operation changed to 25.5 kbps and from 170.0 kbps to 22.7 kbps for in-band operation. UL multi-tone data rate decreased as well from 250.0 kbps to 62.5 kbps across all operation modes. [5, p. 312 – 313]

***Table 15.*** *NB-IoT peak data rate [5, p. 314].*

| | **Stand-alone [kbps]** | **In-band [kbps]** | **Guard-band [kbps]** |
|---|---|---|---|
| NPDSCH | 25.5 | 25.5 | 25.5 |
| NPUSCH multi-tone | 62.5 | 62.5 | 62.5 |
| NPUSCH single-tone (15 kHz) | 15.6 | 15.6 | 15.6 |
| NPUSCH single-tone (3.75 kHz) | 4.8 | 4.8 | 4.8 |

The latency requirement for NB-IoT was that the device is able to deliver an exception report to the network within 10 seconds. The latency results of delivering the 94-byte exception report utilizing the RRC resume procedure are gathered in table 16 and every step of the data transfer process based on the RRC resume procedure are shown in figure 4. In figure 4 the data transfer procedure is divided into four sections: synchronization, connection setup, data transmission and connection release. The time it takes to perform all the steps listed in figure 4 in different modes of operation and in different coverage cases is what determines the values listed in table 16. From table 16 can be seen that NB-IoT fulfills the latency requirement even when coupling loss is 164 dB with maximum latency of 5.1 s for stand-alone mode, 8.0 s for guard band mode and 8.3 s for in-band mode. The minimum latency achieved for all modes of operation with a coupling loss of 144 dB was 0.3 s. [5, p. 314 – 316]

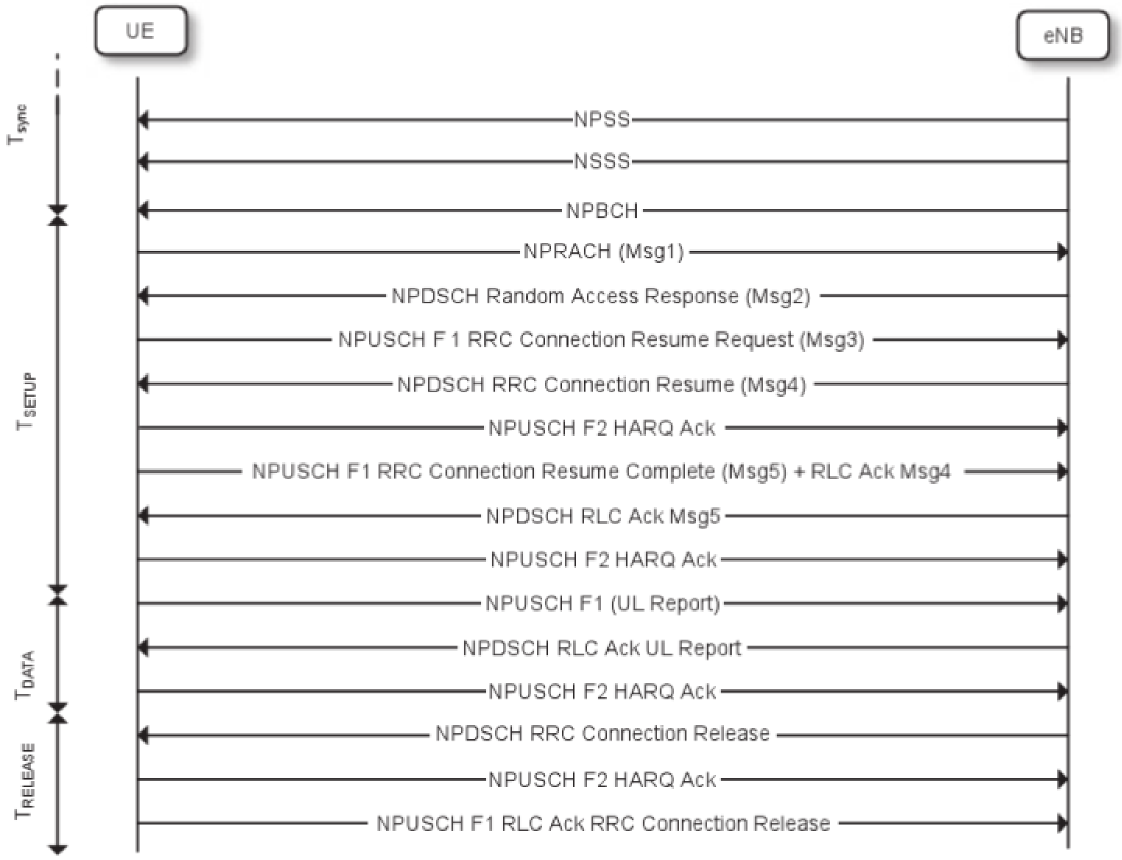


***Figure 4.*** *NB-IoT data transfer based on the RRC resume procedure [5, p. 315].*

***Table 16.*** *NB-IoT latency. [5, p. 316].*

| Coupling Loss [dB] | Stand-alone | Guard-band [s] | In-band [s] |
|---|---|---|---|
| 144 | 0.3 | 0.3 | 0.3 |
| 154 | 0.7 | 0.9 | 1.1 |
| 164 | 5.1 | 8.0 | 8.3 |

The battery life target for NB-IoT devices was set to 10 years on a battery delivering 5 Wh. The battery life for NB-IoT can be evaluated using a simple traffic model with varying packet sizes and arrival rates. The packet sizes used in this evaluation on top of the Packet Data Convergence Protocol (PDCP) layer were 200 and 50 bytes for the UL report with 65 bytes for the DL application acknowledgement. The arrival rates considered were once every two hours and once every day. In addition to packet sizes and arrival rates, the battery life of the device is also affected by the power consumption levels listed in figure 17 and the packet flow used in the evaluation that is shown in figure 5. [5, p. 316 – 317]

***Table 17.*** *NB-IoT power consumption levels [5, p. 317].*

| Tx, 23 dBm | Rx | Light Sleep | Deep Sleep |
|---|---|---|---|
| 500 mW | 80 mW | 3 mW | 0.015 mW |

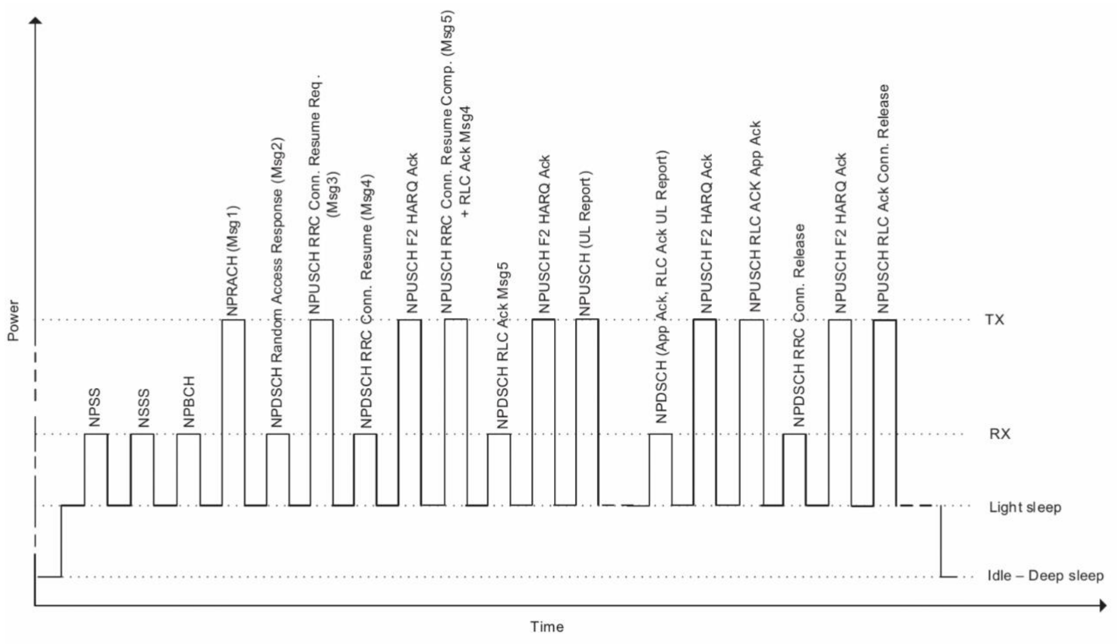


***Figure 5.*** *Packet flow of the battery life evaluation [5, p. 318].*

Using the packet flow depicted in figure 5 and the power consumption levels shown in table 17 in combination with the aforementioned packet sizes and intervals, the battery life of the NB-IoT device is evaluated. The results are gathered in table 18. From table 18 can be seen that with 24-hour reporting interval the battery life target of 10 years can be reached in every instance. However, with a reporting interval of two hours the battery life in extreme coverage situations fall short of the 10-year target across all modes of operation. [5, p. 318]

***Table 18.*** *NB-IoT battery life for stand-alone (S), guard-band (G) and in-band (I) [5, p. 318].*

| Reporting Interval [Hours] | DL Packet Size [Bytes] | UL Packet Size [Bytes] | Battery Life [Years] | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 144 dB CL | | | 154 dB CL | | | 164 dB MCL | | |
| | | | S | G | I | S | G | I | S | G | I |
| 2 | 65 | 50 | 22.2 | 22.1 | 22.1 | 13 | 12.6 | 12.3 | 3.0 | 2.7 | 2.6 |
| | | 200 | 20.0 | 20.0 | 20.0 | 7.9 | 7.8 | 7.7 | 1.4 | 1.3 | 1.3 |
| 24 | | 50 | 36.2 | 36.1 | 36.1 | 33.0 | 32.8 | 32.6 | 19.3 | 18.4 | 18.0 |
| | | 200 | 35.6 | 35.6 | 35.6 | 29.0 | 28.9 | 28.7 | 11.8 | 11.5 | 11.3 |

The objective for NB-IoT capacity in release 13 was set to 60,680 devices/km$^2$ with 52,547 devices/cell. The capacity of NB-IoT was simulated assuming a network load up to 110,000 users per carrier in reference [5] for both anchor carriers and nonanchor carriers. Relevant simulation assumptions are gathered in table 19. When considering system capacity with 1% outage, meaning that 99% of all users can be served in any given time, a capacity of 67,000 devices/km$^2$ can be attained for the anchor carrier which corresponds to 7.5 user arrivals per second. Nonanchor carriers at the same outage percentage of 1% can reach 110,000 devices/km$^2$, corresponding to 12.3 user arrivals per second. The results are gathered in table 20 and it shows that NB-IoT is able to reach the capacity objective of 60,680 devices/km$^2$. The disparity between the capacity results for anchor and nonanchor carriers is explained by nonanchor carriers having no DL overhead when it comes to synchronization and broadcast channels thus resulting in a fairly even resource distribution between DL and UL. [5, p. 319 - 322]

***Table 19.*** *Simulation assumptions for NB-IoT capacity [5, p. 320].*

| **Parameter** | **Model** |
|---|---|
| Cell structure | Hexagonal grid with 3 sectors per size |
| Cell intersite distance | 1732 m |
| Frequency band | 900 MHz |
| LTE system bandwidth | 10 MHz |
| Frequency reuse | 1 |
| Base station transmit power | 46 dBm |
| Power boosting | 6 dB on the anchor carrier<br>0 dB on nonanchor carriers |
| Base station antenna gain | 18 dBi |
| Operation mode | In-band |
| Device transmit power | 23 dBm |
| Device antenna gain | –4 dBi |
| Device mobility | 0 km/h |
| Pathloss model | $120.9 + 37.6 \times \log_{10}(d)$, with d being the base station to device distance in km |
| Shadow fading standard deviation | 8 dB |
| Shadow fading correlation distance | 110 m |
| Anchor carrier overhead from mandatory downlink transmissions | NPSS, NSSS, NPBCH mapped to 25% of the downlink subframes. |
| Anchor carrier overhead from mandatory uplink transmissions | NPRACH mapped to 7% of the uplink resources. |

***Table 20.*** *NB-IoT capacity [5, p. 322].*

| **Case** | **Connection Density at 1% Outage [devices/km$^2$]** | **Arrival Rate at 1% Outage [connections/s]** |
|---|---|---|
| NB-IoT anchor | 67,000 | 7.5 |
| NB-IoT nonanchor | 110,000 | 12.3 |

A major aspect of NB-IoT development was achieving low module cost through ultra-low device complexity, making it more appealing for low-range MTC applications. Low complexity of NB-IoT is attained with design parameters listed in table 21. Table 21 lists key aspects such as Frequency Division Duplex (FDD) and half duplex operation, use of one receive antenna, option for lower power class of 20 dBm, maximum bandwidth of 180 kHz, QPSK modulation, maximum DL TBS of 680 bits and peak instantaneous DL data rate of 226.7 kbps. [5, p. 323 – 324]

***Table 21.*** *NB-IoT device overview [5, p. 324].*

| Parameter | Value |
|---|---|
| Operation modes | FDD |
| Duplex modes | Half duplex |
| Half duplex operation | Type B |
| Device RX antennas | 1 |
| Power class | 20, 23 dBm |
| Maximum bandwidth | 180 kHz |
| Highest downlink modulation order | QPSK |
| Highest uplink modulation order | QPSK |
| Maximum number of supported DL spatial layers | 1 |
| Maximum DL TBS size | 680 bits |
| Number of HARQ processes | 1 |
| Peak instantaneous DL physical layer data rate | 226.7 kbps |
| DL channel coding type | TBCC |
| Physical layer memory requirement | 2112 soft channel bits |
| Layer 2 memory requirement | 4000 bytes |

Physical layer memory requirement of NB-IoT is determined by the maximum DL TBS of 680 bits, 24 cyclic redundancy bits and the encoding with LTE rate-1/3 Tail-Biting Convolutional Code (TBCC) resulting in 2112 soft channel bits. Notable aspects regarding baseband complexity are the requirement for NPSS synchronization during cell selection as well as the fast Fourier transform and decoding operations performed in connected mode. [5, p. 323]

## 2.3 EC-GSM-IoT

### 2.3.1 Background

Extended Coverage Global System for Mobile Communications Internet of Things (EC-GSM-IoT) is an enhanced version of the GSM radio access network specified by 3GPP in its release 13 in 2016. EC-GSM-IoT offers reliable Machine Type Communications (MTC) to low-end IoT applications. It also provides an easy way for devices using GPRS/EDGE to transition to a more recent and enhanced technology. [5, s. 32 – 36] [15]

EC-GSM-IoT is based on the now 25-year-old technology GSM. Despite its age, GSM networks are still in use in almost every country in the world and it is estimated that GSM reaches over 90% of the world’s population. Over the years

GSM has had some improvements such as the introduction of packet switched services in the form of General Packet Radio Service (GPRS), enabling to only reserve resources when there is data to send. Due to the success of GPRS another packet switched service called Enhanced Data Rates for GSM Evolution (EDGE) was introduced, providing higher data rates through higher order modulation speed and improved protocol handling. The main drawback with GSM nowadays is that it’s being overshadowed by modern technologies and their features, resulting in refarming of the GSM spectrum. It will take some time for GSM to truly fade away mainly due to its global presence and contractual obligations. However, many network providers are beginning to steer away from the technology. [5, s. 33 – 35]

Because of the requirements of modern IoT, 3GPP decided to build upon the mature GSM technology and all its improvements by developing EC-GSM-IoT. EC-GSM-IoT improves GSM by increasing coverage and battery lifetime while maintaining low device cost. Additionally, EC-GSM-IoT operates in a tight frequency spectrum thus minimizing conflicts in spectrum usage with other technologies. EC-GSM-IoT also improves end user security to a 4G level and supports a massive number of IoT devices in the network while ensuring backward compatibility with existing GSM network and devices. [5, s. 36]

### 2.3.2 Performance

The design objectives set during the 3GPP study on Cellular System Support for Ultra-Low Complexity and Low Throughput Internet of Things apply for both EC-GSM-IoT and NB-IoT and they include: [5, p. 106]

- Maximum Coupling Loss (MCL) of 164 dB
- Minimum data rate of 160 bps
- Service latency of 10 seconds
- Device battery life of up to 10 years
- System capacity of 60,000 devices/km$^2$
- Ultra-low device complexity

Furthermore, EC-GSM-IoT is required to function within a bandwidth of 600 kHz. Regarding coverage, a key aspect of EC-GSM-IoT development was to increase its coverage by 20 dB compared to General Packet Radio Service (GPRS) thus reaching an MCL of 164 dB. [5, p. 106]

To reach the desired coverage level, the logical channels of EC-GSM-IoT need to have adequate performance. For synchronization channels i.e. Frequency Correction Channel (FCCH) and Extended Coverage Synchronization Channel (EC-SCH), adequate performance means a short synchronization time between a device and a cell, enabling device operation with good latency and power efficiency. For control and broadcast channels Extended Coverage Packet Associated Control Channel (EC-PACCH), Extended Coverage Access Grant Channel (EC-AGCH), Extended Coverage Paging Channel (EC-PCH), Extended Coverage Broadcast Channel (EC-BCCH) and Extended Coverage Common Control Channel (EC-CCCH), a Block Error Rate (BLER) of 10% is considered enough to support efficient network operation. For the Extended Coverage Random Access Channel (EC-RACH), a BLER of 20% is adequate. For traffic channels such as Extended Coverage Packet Data Traffic Channel (EC-PDTCH), the performance is tied to its data rate. [5, p. 107 – 108]

The performance of the logical channels of EC-GSM-IoT are simulated in reference [5] and the simulation assumptions used are shown in table 22. The Modulation and Coding Scheme 1 (MCS-1) assumed in the simulations uses Gaussian Minimum Shift Keying (GMSK) modulation and a code rate of ~0.5. [5, p. 109].

***Table 22.*** *EC-GSM-IoT coverage simulation assumptions [5, p. 109].*

| **Parameter** | **Value** |
|---|---|
| Frequency band | 900 MHz |
| Propagation condition | Typical Urban (TU) |
| Fading | Rayleigh, 1 Hz |
| Device initial oscillator inaccuracy | 20 ppm (applied in FCCH/EC-SCH evaluations) |
| Device frequency drift | 22.5 Hz/s |
| Device NF | 5 dB |
| Base station NF | 3 dB |
| Device power class | 33 or 23 dBm |
| Base station power class | 43 dBm |
| Modulation and coding scheme | MCS-1 |

The downlink coverage performance of EC-GSM-IoT is shown in table 23 and uplink coverage performance is shown in table 24. Tables 23 & 24 present the maximum attainable coupling loss at the specified BLER percentage for control and broadcast channels and level of performance at 164 dB MCL for other channels. [5, p. 109]

***Table 23.*** *EC-GSM-IoT downlink coverage performance [5, p. 110].*

| **#** | **Logical channel name** | **EC-PDTCH/D** | | **EC-PACCH/D** | **EC-CCCH/D** | **EC-BCCH** | **EC-SCH** | **FCCH/EC-SCH** |
|---|---|---|---|---|---|---|---|---|
| 1 | Performance | 0.5 kbps[a] | 2.3 kbps[b] | 10% BLER | 10% BLER | 10% BLER | 1.15 s | |
| Transmitter | | | | | | | | |
| 2 | Total BS Tx power [dBm] | 43 | 43 | 43 | 43 | 43 | 43 | 43 |
| Receiver | | | | | | | | |
| 3 | Thermal noise [dBm/Hz] | –174 | –174 | –174 | –174 | –174 | –174 | –174 |
| 4 | Receiver noise figure [dB] | 5 | 5 | 5 | 5 | 5 | 5 | 5 |
| 5 | Interference margin [dB] | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6 | Channel bandwidth [kHz] | 271 | 271 | 271 | 271 | 271 | 271 | 271 |
| 7 | Effective noise power [dBm] = (3) + (4) + (5) + 10 $\log_{10}$(6) | –114.7 | –114.7 | –114.7 | –114.7 | –114.7 | –114.7 | –114.7 |
| 8 | Required DL SINR [dB] | –6.3 | 3.7 | –6.4 | –8.8 | –6.5 | –8.8 | –6.3 |
| 9 | Receiver sensitivity [dBm] = (7) + (8) | –121 | –111 | –121.1 | –123.5 | –121.2 | –123.5 | –121 |
| 10 | Receiver processing gain [dB] | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 11 | MCL [dB] = (2) – (9) + 10 | 164 | 154 | 164.1 | 166.5 | 164.2 | 166.5 | 164 |
| [a]*Assuming a 33 dBm device feedbacks the EC-PACCH/U.* | | | | | | | | |
| [b]*Assuming a 23 dBm device feedbacks the EC-PACCH/U.* | | | | | | | | |

***Table 24.*** *EC-GSM-IoT uplink coverage performance [5, p. 111].*

| # | Logical channel name | EC-PDTCH/U | | EC-PACCH/U | | EC-RACH | |
|---|---|---|---|---|---|---|---|
| 1 | Performance | 0.5 kbps | 0.6 kbps | 10% BLER | 10% BLER | 20% BLER | 20% BLER |
| Transmitter | | | | | | | |
| 2 | Total device Tx power [dBm] | 33 | 23 | 33 | 23 | 33 | 23 |
| Receiver | | | | | | | |
| 3 | Thermal noise [dBm/Hz] | –174 | –174 | –174 | –174 | –174 | –174 |
| 4 | Receiver noise figure [dB] | 3 | 3 | 3 | 3 | 3 | 3 |
| 5 | Interference margin [dB] | 0 | 0 | 0 | 0 | 0 | 0 |
| 6 | Channel bandwidth [kHz] | 271 | 271 | 271 | 271 | 271 | 271 |
| 7 | Effective noise power [dBm] = (3) + (4) + (5) + 10 $\log_{10}$(6) | –116.7 | –116.7 | –116.7 | –116.7 | –116.7 | –116.7 |
| 8 | Required UL SINR [dB] | –14.3 | –14.3 | –14.3 | –14.3 | –15 | –15 |
| 9 | Receiver sensitivity [dBm] = (7) + (8) | –131.0 | –131.0 | –131.0 | –131.0 | –131.7 | –131.7 |
| 10 | Receiver processing gain [dB] | 0 | 0 | 0 | 0 | 0 | 0 |
| 11 | MCL [dB] = (2) – (9) + 10 | 164.0 | 154.0 | 164.0 | 154.0 | 164.7 | 154.7 |

Tables 23 & 24 show that an MCL of 164 dB is attainable for EC-GSM-IoT with a device output power of 33 dBm. When utilizing a device with an output power of 23 dBm the desired MCL is no longer reached. However, lower device output power provides the additional benefit of reduced device complexity. [5, p. 112]

Data rates for EC-GSM-IoT physical layer are shown in tables 25 & 26. As can be seen from the tables 25 & 26, under good coverage conditions EC-GSM-IoT physical layer is capable of a peak data rate of 97.9 kbps for both UL and DL when utilizing the highest modulation and coding scheme Eight Phase Shift Keying (8PSK) and all eight timeslots. When using GMSK as the modulation and coding scheme the peak data rate is reduced to 51.2 kbps. Additionally, the data rate is significantly lower at areas with poor coverage. As can be seen from table 25 at 164 dB CL the data rate drops to 0.5 kbps for both UL and DL. [5, p. 112 – 115]

***Table 25.*** *EC-GSM-IoT physical layer data rates for 33 dBm devices [5, p. 114].*

| | Physical layer data rate | | | Peak physical layer data rate [kbps] | Instantaneous peak physical layer data rate [kbps] |
|---|---|---|---|---|---|
| | 164 dB CL [kbps] | 154 dB CL [kbps] | 144 dB CL [kbps] | | |
| Downlink | 0.5 | 3.7 | 45.6 | 97.9 | 489.6 |
| Uplink, 8PSK supported | 0.5 | 2.7 | 39.8 | 97.9 | 489.6 |
| Uplink, GMSK supported | 0.5 | 2.7 | 39.8 | 51.2 | 153.6 |

***Table 26.*** *EC-GSM-IoT physical layer data rates for 23 dBm devices [5, p. 115].*

| | Physical layer data rate | | | Peak physical layer data rate [kbps] | Instantaneous peak physical layer data rate [kbps] |
|---|---|---|---|---|---|
| | 164 dB CL [kbps] | 154 dB CL [kbps] | 144 dB CL [kbps] | | |
| Downlink | – | 2.3 | 7.5 | 97.9 | 489.6 |
| Uplink, 8PSK supported | – | 0.6 | 2.7 | 97.9 | 489.6 |
| Uplink, GMSK supported | – | 0.6 | 2.7 | 51.2 | 153.6 |

The goal for the latency of EC-GSM-IoT was the ability to successfully deliver an exception report within 10 seconds from waking up from a state of deep sleep. The exception report is a 96-byte high priority message specified in 3GPP release 13. The process of sending an exception report is depicted in figure 6. In figure 6 the signaling and packet transfers are divided into three parts: synchronization time $T_{SYNC}$, random access procedure time $T_{RA}$ and data transmit time $T_{DATA}$. [5, p. 115 – 117]

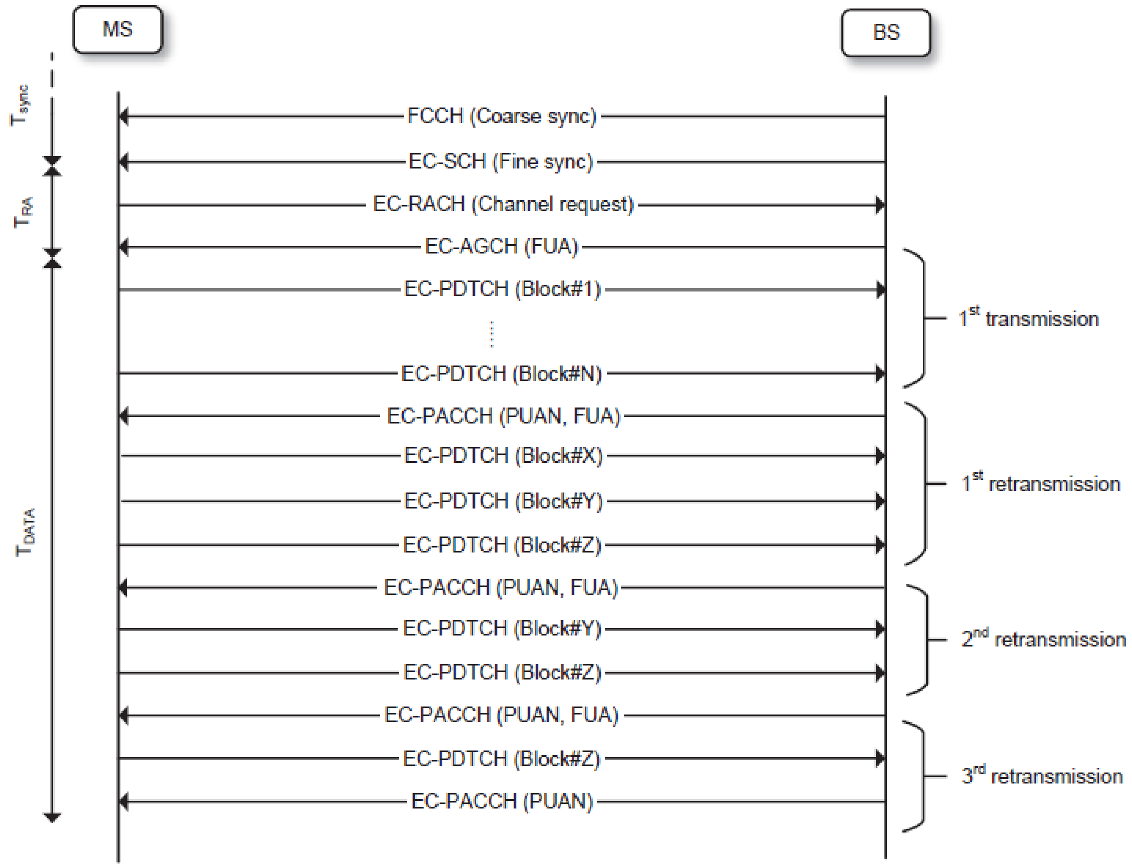


***Figure 6.*** *Exception report procedure for EC-GSM-IoT [2, p. 116].*

Latency evaluation for EC-GSM-IoT are shown in table 27 for both 23 dBm and 33 dBm devices. The evaluations in reference [2] are based on the data structure of the exception report and on the signaling and packet transfer procedure depicted in figure 6. The latency evaluations in table 27 show that EC-GSM-IoT is able to deliver the exception report in under the required 10 seconds with a maximum latency of 5.1 seconds for a 33 dBm device in extreme coverage areas. [2, p. 116 – 118]

***Table 27.*** *EC-GSM-IoT latencies [2, p. 118].*

| Coupling loss [dB] | 23 dBm device [s] | 33 dBm device [s] |
|---|---|---|
| 144 | 1.2 | 0.6 |
| 154 | 3.5 | 1.8 |
| 164 | – | 5.1 |

The design goal for the battery life of EC-GSM-IoT devices was 10 years of operation on a battery delivering 5 Wh. The battery life of EC-GSM-IoT devices is evaluated by having the device transmit either a 50-byte or a 200-byte UL report and then receive a 65-byte DL application acknowledgement. These actions are taken once every two hours or once every 24 hours. The power consumption of different EC-GSM-IoT device states is shown in table 28 and the packet flow used in the battery life evaluation is depicted in figure 7. [2, p. 118 – 119]

***Table 28.*** *EC-GSM-IoT power consumption [2, p. 119].*

| TX, 33 dBm | TX, 23 dBm | RX | Idle and connected mode, light sleep | Idle mode, deep sleep |
|---|---|---|---|---|
| 4.051 W | 0.503 W | 99 mW | 3 mW | 15 mW |

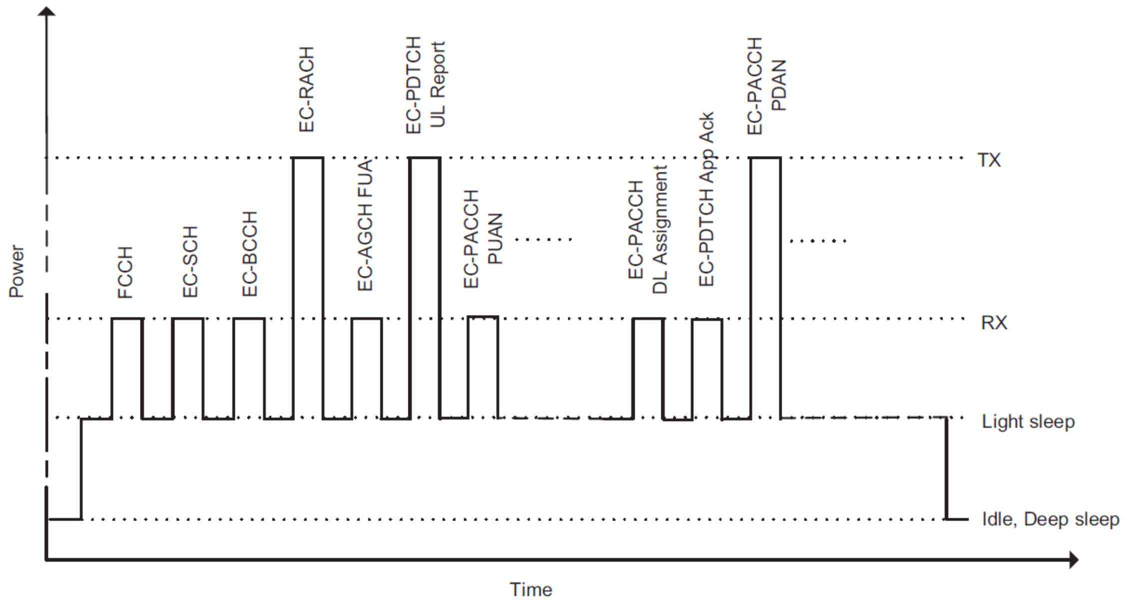


***Figure 7.*** *EC-GSM-IoT packet flow of the battery life evaluation [2, p. 119].*

Taking into consideration the EC-GSM-IoT device power consumption and the assumed packet flow in combination with the aforementioned traffic model, results in the battery lives gathered in tables 29 & 30. The results show that that the battery life goal of 10 years can be reached for the most part with every scenario with decent coverage. However, devices that are in extreme coverage areas with 164 dB CL appear to fall short of the 10-year target when using a two-hour reporting interval.

***Table 29.*** *EC-GSM-IoT battery life evaluation results for 33 dBm devices [2, p. 120].*

| Reporting Interval [h] | DL Packet Size [Bytes] | UL Packet Size [Bytes] | Battery Life [years] | | |
|---|---|---|---|---|---|
| | | | 144 dB CL | 154 dB CL | 164 dB CL |
| 2 | 65 | 50 | 22.6 | 13.7 | 2.8 |
| | | 200 | 18.4 | 8.5 | 1.2 |
| 24 | | 50 | 36.0 | 33.2 | 18.8 |
| | | 200 | 35.0 | 29.5 | 11.0 |

***Table 30.*** *EC-GSM-IoT battery life evaluation results for 23 dBm devices [2, p. 120].*

| Reporting Interval [h] | DL Packet Size [Bytes] | UL Packet Size [Bytes] | Battery Life [years] | |
|---|---|---|---|---|
| | | | 144 dB CL | 154 dB CL |
| 2 | 65 | 50 | 26.1 | 12.5 |
| | | 200 | 22.7 | 7.4 |
| 24 | | 50 | 36.6 | 32.5 |
| | | 200 | 36.0 | 28.3 |

EC-GSM-IoT is expected to support at least 60,680 devices/km$^2$. This capacity expectation is based on deployment in areas such as London, where density can reach 1517 homes/km$^2$ with 40 active devices per household. The capacity of EC-GSM-IoT is evaluated in reference [2] with a traffic scenario that corresponds to a deployment multiple of smart utility meters. Relevant system level simulation assumptions are gathered in table 31. It is also assumed that 80% of all devices independently trigger a 20-200 byte UL report. The packet size of the UL report varies in accordance with Pareto distribution as displayed in figure 8. For the remaining 20% of the devices, it is assumed that the network sends them a 20-byte DL command to which half of the devices are assumed to respond with the aforementioned Pareto distributed UL report. [2, p. 121 – 124]

***Table 31.*** *System level simulation assumptions [2, p. 122 – 123].*

| **Parameter** | **Model** |
|---|---|
| Cell structure | Hexagonal grid with three sectors per site |
| Cell intersite distance | 1732 m |
| Frequency band | 900 MHz |
| System bandwidth | 2.4 MHz |
| Frequency reuse | 12 |
| Frequency channels (ARFCN) per cell | 1 |
| Base station transmit power | 43 dBm |
| Base station antenna gain | 18 dBi |
| Channel mapping | TS0: FCCH, SCH, BCCH, CCCH<br>TS1: EC-SCH, EC-BCCH, EC-CCCH<br>TS2-7: EC-PACCH, EC-PDTCH |
| Device transmit power | 33 or 23 dBm |
| Device antenna gain | –4 dBi |
| Device mobility | 0 km/h |
| Path loss model | $120.9 + 37.6 \times \log_{10}(d)$, with d being the base station to device distance in km |
| Shadow fading standard deviation | 8 dB |
| Shadow fading correlation distance | 110 m |

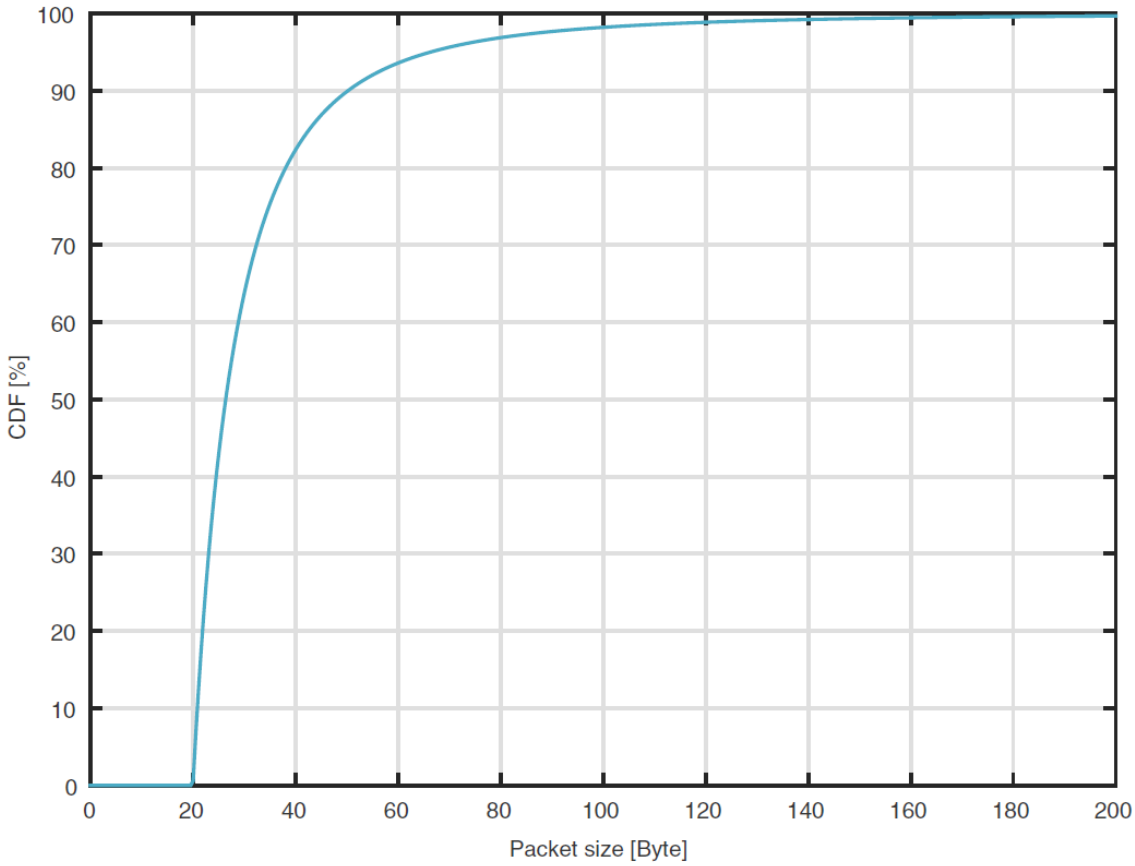


***Figure 8.*** *Pareto distributed UL report size [2, p. 123].*

Different report and network command intervals are examined ranging from once every 24 hours to twice every hour as shown in table 32. Table 32 also shows the device distribution for the different reporting intervals. Using the given assumptions, it can be concluded that with a target of 60,680 devices/km$^2$, which translates to 52,547 devices per cell with a cell intersite distance of 1732 m, around 6.8 devices per cell try to transition from idle to connected mode every second. With this kind of load the capacity of EC-GSM-IoT radio resources are consumed as illustrated in figure 9. Figure 9 shows how EC-CCCH consumes 10% of the available capacity for downlink and slightly less for uplink. EC-PDTCH and EC-PACCH consume 14% of the available resources for 33 dBm devices and 27% for 23 dBm devices. Downlink for these channels use roughly 6% capacity due to an uplink heavy traffic model. For this simulation paging load was not considered on the EC-CCCH/D. These results were obtained while failed connection attempts remained below 0.1% thus indicating that EC-GSM-IoT is able to support substantially higher loads than the simulated 52,547 devices per cell. [2, p. 124 – 126]

***Table 32.*** *Device reporting interval and distribution [2, p. 124].*

| **Device report and network command periodicity [h]** | **Device distribution [%]** |
|---|---|
| 24 | 40 |
| 2 | 40 |
| 1 | 15 |
| 0.5 | 5 |

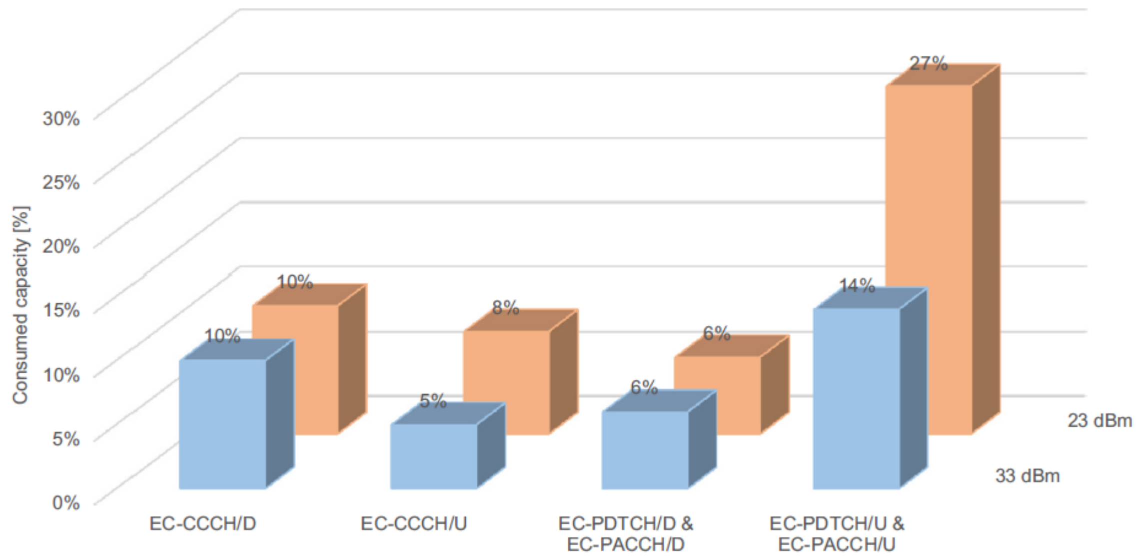


***Figure 9.*** *EC-GSM-IoT radio resources consumed on average to service 52,547 users per cell [2, p. 125].*

Complexity of EC-GSM-IoT was kept low to ensure its competitiveness in the market. Low complexity was achieved through the reduction of procedures, computational complexity and memory requirements of the higher and lower layers. In more detail, a reduction of the protocol stack alleviates memory requirements which was made possible by discarding circuit switched voice support, only mandating MCS-1 to MCS-4, limiting the Radio Link Control (RLC) window size to 16, reducing the amount of supported RLC/Medium Access Control (MAC) messages and procedures as well as not supporting simultaneous UL and DL data transfers. [2, p. 126 – 128]

Compared to GPRS a 66% reduction in computational complexity is achieved due to EC-PDTCH reception consuming an estimated 88 × $10^3$ Digital Signal Processor (DSP) cycles per Time Division Multiple Access (TDMA) frame. ROM and RAM memory reductions of 160 kB are also made possible by reducing the memory size of the DSP. [2, p. 128]

EC-GSM-IoT only supports four global frequency bands which reduces the amount of support needed for different frequency variants of the same device. In addition, EC-GSM-IoT utilizes half-duplex operation which allows for the use of a RX-TX antenna switch in place of a duplexer. [2, p. 129]

## 2.4 Technologies for unlicensed operation

Wireless communication technologies can be divided into two groups based on whether they operate in licensed or unlicensed spectrum. Network operators wanting to utilize the licensed spectrum require a license from the regulatory body of the respective region. These licenses offer exclusive rights to use the selected frequency spectrum within a specific region but may come with obligations such as the requirement to provide network coverage and communication services. [2, p. 328]

Operation in the unlicensed spectrum requires no license, meaning that any device is permitted to transmit within that spectrum assuming that they follow certain regulations constructed to ensure efficient and harmonious spectrum usage. These unlicensed spectrum bands tend to vary between different regions, although bands ranging around 2.4 GHz are quite popular on a global scale. [2, p. 9]

The unlicensed bands ranging around 900 MHz and 2.4 GHz carry additional significance for IoT applications mainly because of the specification of widespread wireless communication standards such as Bluetooth and Wi-Fi for these bands. In addition, bands ranging around 900 Mhz offer beneficial propagation characteristics facilitating good coverage and bands ranging around 2.4 GHz can be considered global, thus offering an attractive option for international operation. [2, p. 328]

The most prominent communication technologies in the unlicensed spectrum used for IoT purposes are IEEE 802.15.4, Wi-Fi HaLow and Bluetooth Low Energy (BLE) for short range communication, and LoRa and Sigfox for long range communication. [2, p. 337 – 342]

### 3.4.1 IEEE 802.15.4

IEEE 802.15.4 is a low-rate wireless personal area network (LR-WPAN) standard that emerged in 2003. It can be used for a variety IoT applications from home automation to smart grids but also serves as a foundation for several application specific protocol stacks. These protocol stacks that build mainly on the physical layer and the MAC of IEEE 802.15.4 include ZigBee, WirelessHART, ISA-100, and Thread. [2, p. 337][16][17]

IEEE 802.15.4 has a coverage range of around 10–20 m, it uses carrier-sense multiple access with collision avoidance (CSMA-CA) for accessing the radio channel and it can utilize three frequency bands: 868 MHz in Europe, 915 MHz in the United States and 2.4 GHz globally. The 868 MHz frequency band has one channel available and uses differential BPSK modulation with direct-sequence-spread-spectrum (DSSS) technology thus achieving a gross data rate of 20 kbps. The 915 MHz frequency band has 10 channels allocated and can reach data rates of 40 kbps. The global frequency band of 2.4 GHz has 16 channels and uses offset QPSK with DSSS to reach gross data rates of 250 kbps. [2, p. 337][18][19]

### 3.4.2 Wi-Fi HaLow

Wi-Fi HaLow, also known as IEEE 802.11ah, is an amendment to the IEEE 802.11 standard with a focus on IoT applications. It is purpose built to support an outdoor application that requires a transmission range up to 1 km at 150 kb/s, thus having more relaxed requirements on data rates compared to many other IEEE 802.11 variants. Wi-Fi HaLow operates in the unlicensed spectrum below 1 GHz allowing longer transmission ranges due to better signal propagation characteristics compared to e.g. Wi-Fi based on the IEEE 802.11 standard that typically operates in 2.4 and 5 GHz frequencies. The specific frequency bands used vary between regions. [2, p. 339][20][21]

The focus of Wi-Fi HaLow development resided in improving its spectral efficiency due to the relative scarcity of unlicensed bandwidth below 1 GHz. It has also seen improvements in the form of multiple new features regarding the reduction of power consumption and an increased number of devices that can associate with one access point. [2, p. 339][20]

The physical layer of Wi-Fi HaLow is based largely on the IEEE 802.11ac variant although with a downscaled bandwidth. Meaning that Wi-Fi HaLow supports various carrier bandwidths in the range of 1–16 MHz. The supported data rates of Wi-Fi HaLow range between 150 kb/s and 347 Mb/s, although the achievable data rates are heavily impacted by factors such as the carrier bandwidth, modulation scheme and coding rate used. [21]

### 3.4.3 Bluetooth Low Energy

Bluetooth Low Energy (BLE) is a low power alternative to classic Bluetooth developed in 2010 by Bluetooth Special Interest Group (BT SIG) as part of the Bluetooth 4.0 specification. The development of BLE was focused on reducing the delay for simple data exchanges and the power consumption for device discovery. [22]

BLE operates in the unlicensed 2.4 GHz frequency band, uses Gaussian Frequency Shift Keying (GFSK) modulation and can reach data rates of up to 1 Mbps. In addition, adaptive frequency hopping is used to minimize interference. The physical layer of BLE has 40 channels defined, three of which are reserved for advertising and the rest are data channels. The purpose of this channel division is to balance the channel contention and delay. [22][23]

BLE supports fragmentation and reassembly of large data packets into small radio frames, thus supporting services with large data packets. In addition, IP connectivity was enabled for BLE in 2014 and end-to-end IPv6 connectivity over BLE has been standardized, therefore enabling IP based IoT applications. [2, p. 338–339]

### 3.4.4 Wireless mesh networks

Wireless mesh networks (WMNs) consist of two or more nodes that share routing protocols to create an interconnected RF pathway from a client (e.g. computer, phone or smart meter) to the internet. These nodes consist of either mesh routers or mesh clients and all of them have the capability to forward data sent from other nodes in the network, thus functioning as a router as well as a host. WMNs are able to dynamically organize and configure themselves as the nodes in the network are capable of automatically establishing and maintaining necessary connectivity. This also means that WMNs are easily scalable as nodes can be deployed incrementally. In addition, mesh routers enable connectivity through various existing wireless networks such as cellular networks and Wi-Fi through the router's gateway/bridge functionality. [4, p. 1][24][25]

WMN architecture can be divided into three categories: backbone WMNs, client WMNs and hybrid WMNs. The backbone WMN is illustrated in figure 10 and it shows how mesh routers form an infrastructure for clients to connect to. [4, p. 2 – 4]

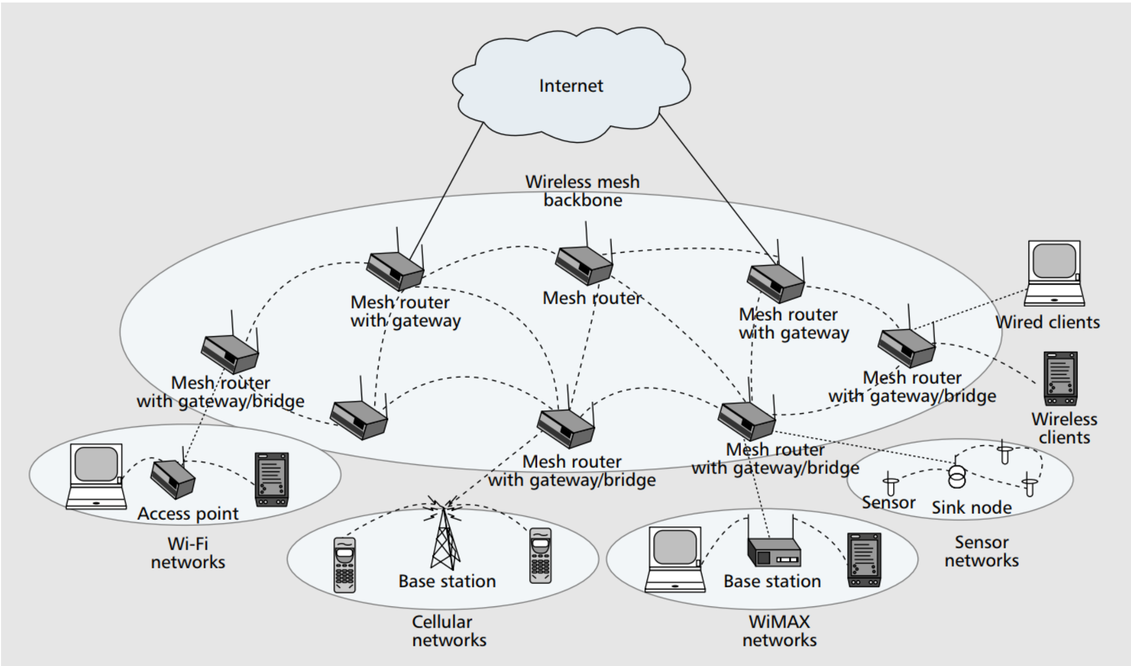


***Figure 10.*** *Backbone wireless mesh network [26].*

Client WMN is illustrated in figure 11 and it shows how client WMNs form peer-to-peer networks comprised of mesh clients. Network architecture of this kind does not require mesh routers to function. However, with no routers present the clients are required to perform tasks such as routing and configuration functionalities. [25, p. 4]

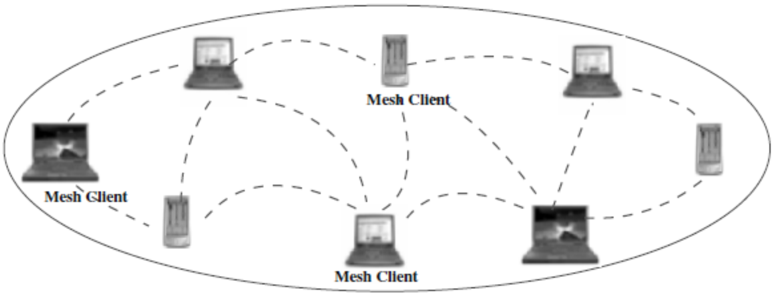


***Figure 11.*** *Client wireless mesh network [4, p. 5].*

Hybrid WMN is illustrated in figure 12. Hybrid WMNs are a combination of backbone and client WMNs. In this type of network mesh clients are able to communicate with other clients as well as mesh routers, thus giving clients access to other networks such as Wi-Fi and cellular networks while maintaining the ability to communicate through peer-to peer communication. [26]

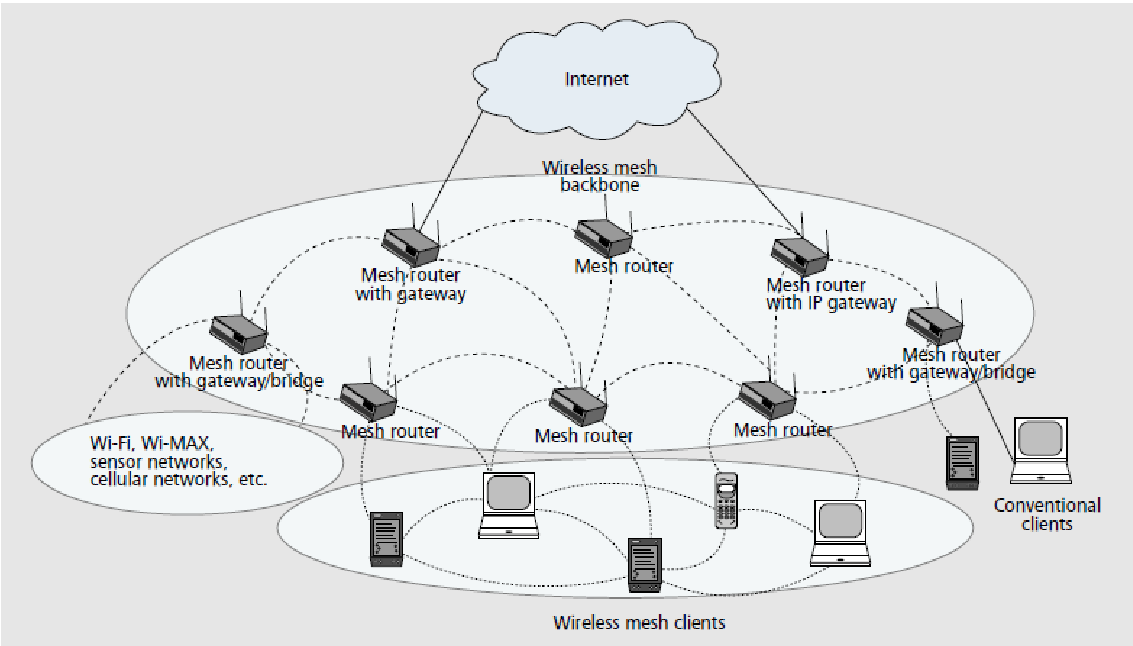


***Figure 12.*** *Hybrid wireless mesh network [26].*

Despite many advancements made towards the betterment of wireless mesh networks, challenges such as scalability still pose limitations. It is easy to expand a WMN by simply adding additional nodes as necessary. However, the size of the network becomes an issue as larger WMNs most often utilize multihop communication that suffers from significant performance degradation as the size of the network grows [4, p. 13].

### 3.4.5 Long-range technologies

Long-range radio systems, although not as common for unlicensed spectrum usage as short-range systems, can be used for IoT applications with low data rates. The most prominent long-range technologies include LoRa and Sigfox. The purpose of these technologies is to offer infrequent and low data rate wireless communication over multiple kilometers. For these technologies, their long range comes at a cost of significantly reduced data rate. [2, p. 342]

LoRa was developed by a French company called Cycleo and it's specified within an industry alliance. LoRa operates in the unlicensed spectrum below 1 GHz and offers data rates ranging from 300 bps to 50 kbps over distances of 2–5 km in urban areas and 15 km in suburban areas. The physical layer of LoRa uses chirp spread-spectrum modulation technology and can utilize one or more radio channels. A major goal of LoRa is to provide secure bidirectional communication. [2, p. 342][27]

Sigfox is a proprietary technology that was developed in 2009 by a French company called Sigfox. Sigfox utilizes unlicensed frequency bands under 1 GHz and offers data rates of 100 bps or 600 bps depending on region. The maximum payload for Sigfox is 12-bytes for the uplink and 8-bytes for the downlink. Sigfox uses Ultra Narrow Band (UNB) radio transmission and the channel bandwidths are 100 Hz or 600 Hz for the uplink depending on region and 1.5 kHz for the downlink. The modulation used for the uplink is Differential Binary Phase-Shift Keying (DBPSK) and for the downlink Gaussian Frequency-Shift Keying (GFSK). The channel access scheme is based on ALOHA, which will lead to many radio packet collisions if channel utilization is not kept low. [2, p. 343][28–30]

# 3. COMPARISON

In this chapter the relevant characteristics of eMTC (aka. LTE-M), NB-IoT and EC-GSM-IoT are compared and the main benefits and disadvantages of licensed and unlicensed technologies are discussed. For NB-IoT, only stand-alone and in-band modes of operation are considered since guard-band mode is very similar to in-band when it comes to performance. [5, p. 345]

## 3.1 Coverage and data rate

All of the aforementioned technologies utilize some form of coverage enhancement techniques to achieve an MCL of 164 dB, a figure significantly higher than those of the many present-day networks such as GSM, UMTS or LTE. Uplink and downlink data rates for the different technologies are shown in figures 13 & 14. Figures 13 & 14 detail data rates in different scenarios, taking into consideration instantaneous peak rates, peak rates and effects of coverage on data rates. The instantaneous peak data rate shows the maximum achievable data rate for the data channels and does not factor in delays stemming from scheduling and control signaling. For the other data rates listed in figures 13 & 14, these latencies are taken into account thus showing the effective physical layer data rates. [5, p. 345 – 346]

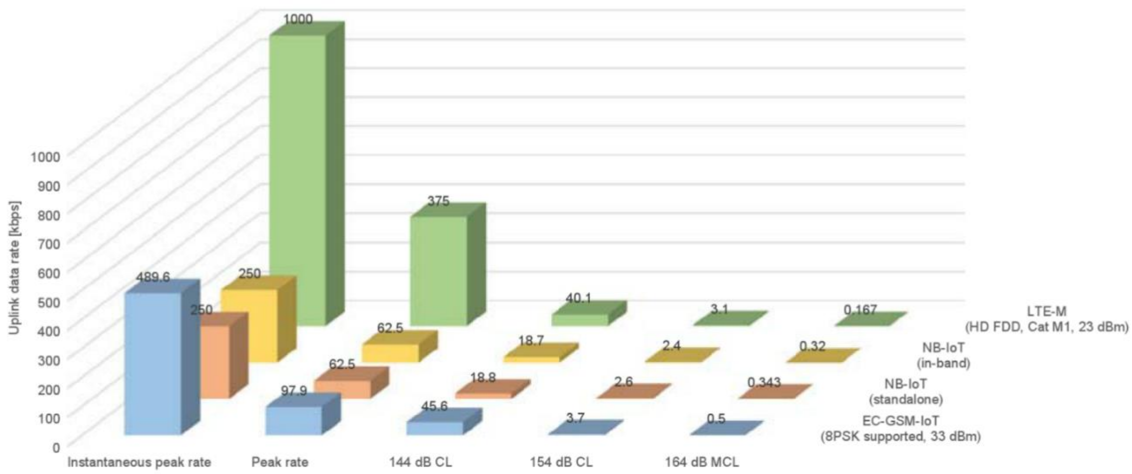


***Figure 13.*** *UL data rate comparison [5, p. 345].*

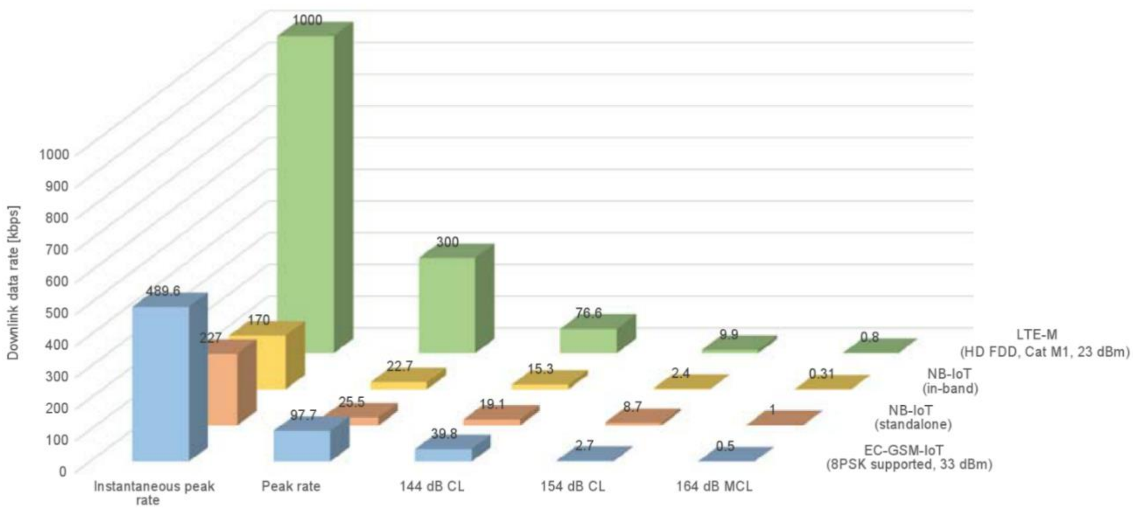


***Figure 14.*** *DL data rate comparison [5, p. 346].*

For this comparison, half-duplex operation is used for all technologies. Although, eMTC also supports full-duplex operation granting significantly higher data rates with a peak data rate of almost 1 Mbps. It should also be noted that EC-GSM-IoT achieves an MCL of 164 dB by using a higher device power class of 33 dBm compared to the device power class of 23 dBm for eMTC and NB-IoT. [5, p. 346]

Analyzing figures 13 & 14 reveals that data rates for eMTC are substantially higher for both UL and DL than the corresponding data rates for NB-IoT and EC-GSM-IoT, especially in areas with decent coverage. In extreme coverage areas the uplink data rate is heavily dependent on device output power and since the device power classes are relatively similar between the different technologies the differences in data rates become smaller. NB-IoT, eMTC and EC-GSM-IoT all surpass the data rate of 160 bps at 164 dB MCL as required by the 3GPP. [5, p. 346]

## 3.2 Latency

Figure 15 shows the latencies for eMTC, NB-IoT and EC-GSM-IoT under several coverage levels. The latencies depicted in figure 15 are evaluated with the use of an 85-byte infrequent high-priority message called an exception report. [5, p. 347]

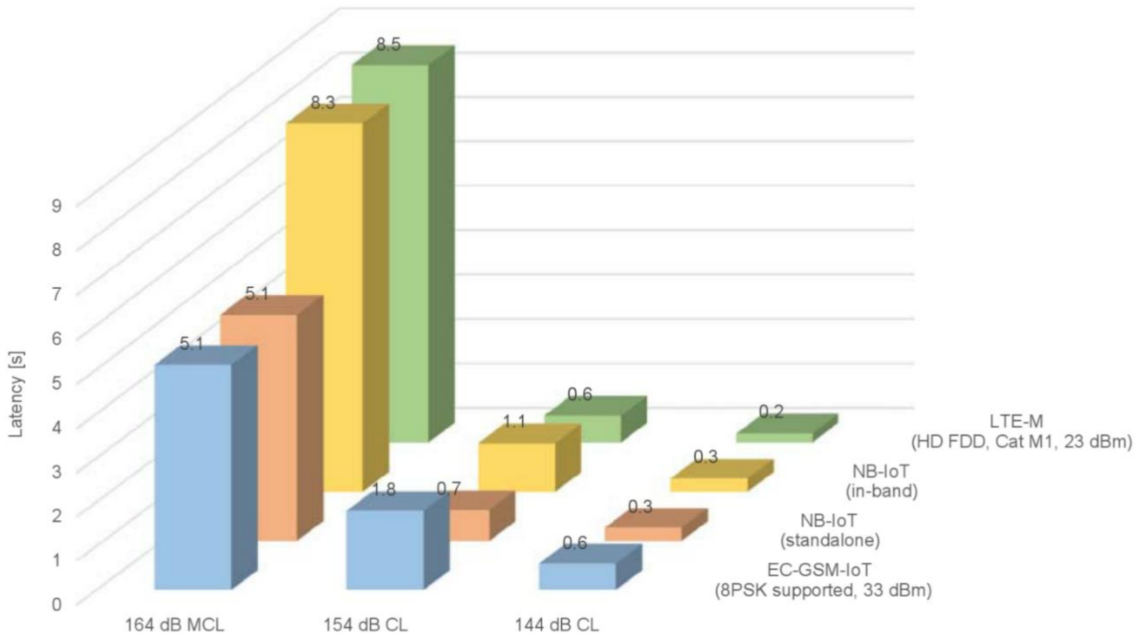


***Figure 15.*** *Latency comparison [5, p. 347].*

The latency requirement for the different technologies set by 3GPP in release 13 is 10 s, a requirement that all three technologies are able to achieve. Figure 15 reveals that EC-GSM-IoT has low latencies even with a coupling loss of 164 dB, mainly due to its relatively high device output power. NB-IoT also achieves low latencies even in extreme coverage areas due to its high power usage for downlink channels. Both eMTC and NB-IoT in in-band mode have higher latencies with 164 dB MCL compared to the other technologies. However, in areas with decent coverage eMTC can achieve comparatively lower latencies due to its high data rate. [5, p. 347]

## 3.3 Battery life

Figure 16 shows the battery lifetimes of different technologies when transmitting a 200-byte message once every 24 hours, assuming a device with a battery capacity of 5 Wh and a 45% - 50% amplifier efficiency. The goal for eMTC, NB-IoT and EC-GSM-IoT battery lives set by 3GPP was 10 years with 164 dB MCL. With the given parameters, only eMTC is unable to reach the set goal as can be seen from figure 16. However, with different parameters such as a 50-byte message instead of 200-byte, the battery life increases notably as can be seen from the summary of the battery lives of different technologies in various scenarios in table 33. [5, p. 348]

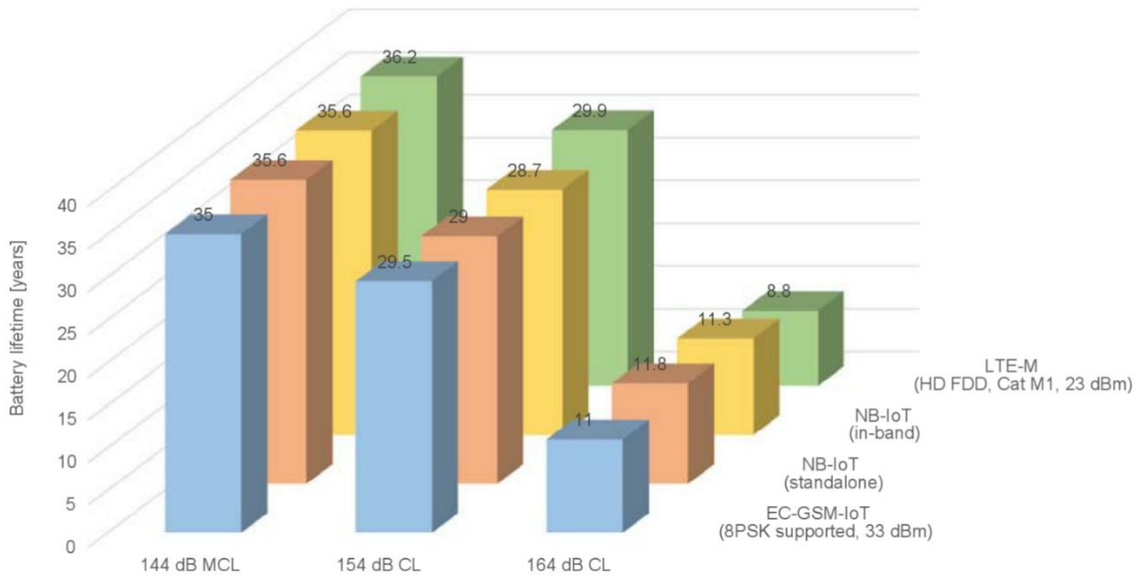


***Figure 16.*** *Battery-life comparison [5, p. 348].*

***Table 33.*** *Battery lives under various scenarios [5, p. 349].*

| | Reporting Interval | DL Packet Size | UL Packet Size | Battery Life (Years) | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | 144 dB CL | | 154 dB CL | | 164 dB CL | |
| LTE-M HD-FDD CAT M1 23 dBm | 2 h | 65 bytes | 50 bytes | 23.7 | | 13.9 | | 2.0 | |
| | | | 200 bytes | 22.3 | | 8.7 | | 0.9 | |
| | 24 h | | 50 bytes | 36.5 | | 33.4 | | 15.5 | |
| | | | 200 bytes | 36.2 | | 29.9 | | 8.8 | |
| Stand-alone (S), In-band (I) | | | | S | I | S | I | S | I |
| NB-IoT 23 dBm | 2 h | 65 bytes | 50 bytes | 22.2 | 22.1 | 13.0 | 12.3 | 3.0 | 2.6 |
| | | | 200 bytes | 20.0 | 20.0 | 7.9 | 7.7 | 1.4 | 1.3 |
| | 24 h | | 50 bytes | 36.2 | 36.1 | 33.0 | 32.6 | 19.3 | 18.0 |
| | | | 200 bytes | 35.6 | 35.6 | 29.0 | 28.7 | 11.8 | 11.3 |
| EC-GSM-IoT 8PSK supported 33 dBm | 2 h | 65 bytes | 50 bytes | 22.6 | | 13.7 | | 2.8 | |
| | | | 200 bytes | 18.4 | | 8.5 | | 1.2 | |
| | 24 h | | 50 bytes | 36.0 | | 33.2 | | 18.8 | |
| | | | 200 bytes | 35.0 | | 29.5 | | 11.0 | |

Figure 16 and table 33 show that in areas with better coverage the battery lives are vastly increased. This is because the discussed technologies mainly save power by staying in different power saving modes as long as possible and when poor coverage forces the devices to retransmit data, the device is unable to stay in power saving mode, thus increasing the power consumption of the device considerably. Other significant contributing factors are reporting interval and UL packet size [5, p. 348]

## 3.4 Device complexity

Low cost through low device complexity was a key factor in the development of all three technologies. The most relevant device attributes contributing to low cost in these technologies are: [5, p. 349 – 350]

- Bandwidth
- Data rate
- Device power class
- Number of antennas
- Duplex modes

With reduced bandwidths, the use of wide-band front ends is no longer required, thus providing a significant cost reduction. The limited peak data rates allow for a relatively relaxed requirements for memory and data processing for the devices and the use of a single receive antenna lower the device complexity even further. Additionally, the support for lower power classes allow for the use of cheaper power amplifiers and the support for Half-Duplex Frequency-Division Duplex (HD-FDD) operation avoids the use of costly duplex filters. Although eMTC also supports Full-Duplex Frequency-Division Duplex (FD-FDD) and Time-Division Duplex (TDD). The relevant attributes concerning device complexity of the technologies in question are summarized in table 34. [5, p. 349 – 350]

***Table 34.*** *Device complexity comparison [5, p. 349 – 350].*

| | **eMTC** | **NB-IoT** | **EC-GSM-IoT** |
|---|---|---|---|
| Bandwidth | 1.4 Mhz | 180 kHz | 200 kHz |
| Peak data rate | 1 Mbps | 300 kbps | 500 kbps |
| Power class | 20, 23 dBm | 14, 20, 23 dBm | 23, 33 dBm |
| Number of antennas | 1 | 1 | 1 |
| Duplex modes | HD-FDD, FD-FDD, TDD | HD-FDD | HD-FDD |

The device complexity of each technology is discussed in more detail in their respective chapters, but the defining characteristics of each technology can be found from table 34.

## 3.5 Capacity

The capacity requirement for eMTC, NB-IoT and EC-GSM-IoT was set to 60,680 devices/km$^2$ by 3GPP in release 13. The simulation assumptions used to determine the capacity of each technology can be found from the performance section of each respective technology. The simulation results for the capacity evaluation can be found in table 35. Using a traffic model where devices on average transmit an autonomous report every ~128.5 min, EC-GSM-IoT is able to achieve ~6.8 message arrivals per second per cell with the percentage of failed access attempts remaining below 0.1%. The 6.8 message arrival rate corresponds to the required capacity of 60,680 devices/km$^2$, meaning that EC-GSM-IoT fulfills the capacity requirement and with a more relaxed percentage on failed access attempts can even surpass it. [5, p. 350 – 351]

***Table 35.*** *Capacity comparison [5, p. 350 – 351].*

| | **Connection density at 0.1% outage (devices/km$^2$)** | **Arrival rate at 0.1% outage (connections/s)** |
|---|---|---|
| EC-GSM-IoT | 60,68 | 6.8 |
| | **Connection density at 1% outage (devices/km$^2$)** | **Arrival rate at 1% outage (connections/s)** |
| eMTC | 361,000 | 40.3 |
| NB-IoT anchor | 67,000 | 7.5 |
| NB-IoT nonanchor | 110,000 | 12.3 |

Similar analysis was performed for eMTC and NB-IoT although with a 1% failed access attempt percentage. As can be seen from table 35 eMTC managed to achieve an arrival rate of 40.3 connections/s corresponding to 361,000 devices/km$^2$. NB-IoT achieved 7.5 connections/s on an anchor carrier corresponding to 67,000 devices/km$^2$ and 12.3 connections/s on a nonanchor carrier corresponding to 110,000 devices/km$^2$. According to the simulations, all three technologies fulfill the capacity requirement set by 3GPP and with a sufficiently relaxed requirement on failed access attempt percentage they can surpass it with a significant margin. [5, p. 350 – 351]

## 3.6 Licenced and unlicenced technologies

One of the major aspects of licensed technologies is that the network connectivity and the infrastructure behind it are maintained by independent operators. Meaning that new IoT applications can be deployed essentially anywhere without the need to install, manage and operate an IoT connectivity solution. The same can't be said for many technologies operating in the unlicensed spectrum. Although technologies such as Sigfox do offer an operator model for end-to-end connectivity, thus providing end users dedicated Sigfox infrastructure, many unlicensed technologies require substantial effort from the end user to install, manage and operate the necessary infrastructure for their IoT connectivity solutions. [2, p. 344]

Many of the technologies operating in the unlicensed spectrum are proprietary and therefore do not require extensive and long standardization processes providing a fast time to market. Although it also raises questions on their long-term support and viability, since they are heavily dependent on a select few market players. In comparison, licensed cellular technologies such as eMTC, NB-IoT and EC-GSM-IoT, that are based on global standards tend to offer reliable long-term solutions and are supported by various industry proponents. [2, p. 344]

Consistency and reliability of the licensed cellular technologies in addition to standardization also stem from them having deployment plans made over decades on infrastructure that is widely available and has established itself as an essential part of modern society. Furthermore, these technologies operate in the licensed spectrum where channel interference is coordinated and radio resources are managed along with full quality of life support. Technologies operating in the unlicensed spectrum tend to be more prone to interference and quality of life support is not guaranteed to be available. Unlicensed frequency bands do have regulations in place to reduce interference such as limitations to the effective radiated power of transmitting devices. However, for long-range communication this can cause asymmetric link budgets between the uplink and downlink especially in non-line-of-sight propagation conditions. [2, p. 344][31]

Scalability issues will also come into play for unlicensed technologies targeting long-range communication due to ever increasing number of transmitting devices under a single base station. Since many of those devices are going to use different communication technologies that utilize the same unlicensed spectrum, long-range devices having low receiver sensitivity will perceive these other transmissions as interference. In reference [31], a prediction is made that these LPWA technologies utilizing the unlicensed spectrum will lose their viability as time goes on and the number of transmitting devices grow. [31]

One drawback for licensed cellular technologies is the relative rigid nature of their network infrastructure. Meaning that in cases of insufficient coverage for a specific IoT use case, implementation of additional infrastructure may be easier, faster and more flexible when using unlicensed technology for a dedicated deployment instead of involving a network operator. [2, p. 345]

# 4. REQUIREMENTS OF AIDON

Since Aidon provides metering infrastructure to multiple energy distribution systems, an efficient and reliable communication technology is of paramount importance. Currently Aidon offers several communication options between its Energy Service Devices (ESDs), Multi-Connectivity Devices (MCDs) and Aidon Head-End System (HES) as depicted in figure 17. [32]

In the Aidon network, ESDs can function as RF slave or RF master devices. Slave devices only communicate with other devices in the vicinity while master devices are also capable of sending data to Aidon HES. MCDs lack the metering capabilities of ESDs; however, they can be used to extend the radio network coverage and capacity as they can function as an RF slave or RF master device. [32]

A common communication solution for Aidon metering network infrastructure is for slave devices to form an RF mesh network amongst themselves and a master device which in turn forwards the relevant data to Aidon HES through wireless cellular networks (2G/3G/4G) or via an ethernet network. Additionally, ESDs can communicate amongst themselves through an RS-485 loop network. Possible communication solutions also include point-to-point connections between the ESDs and Aidon HES. [32]

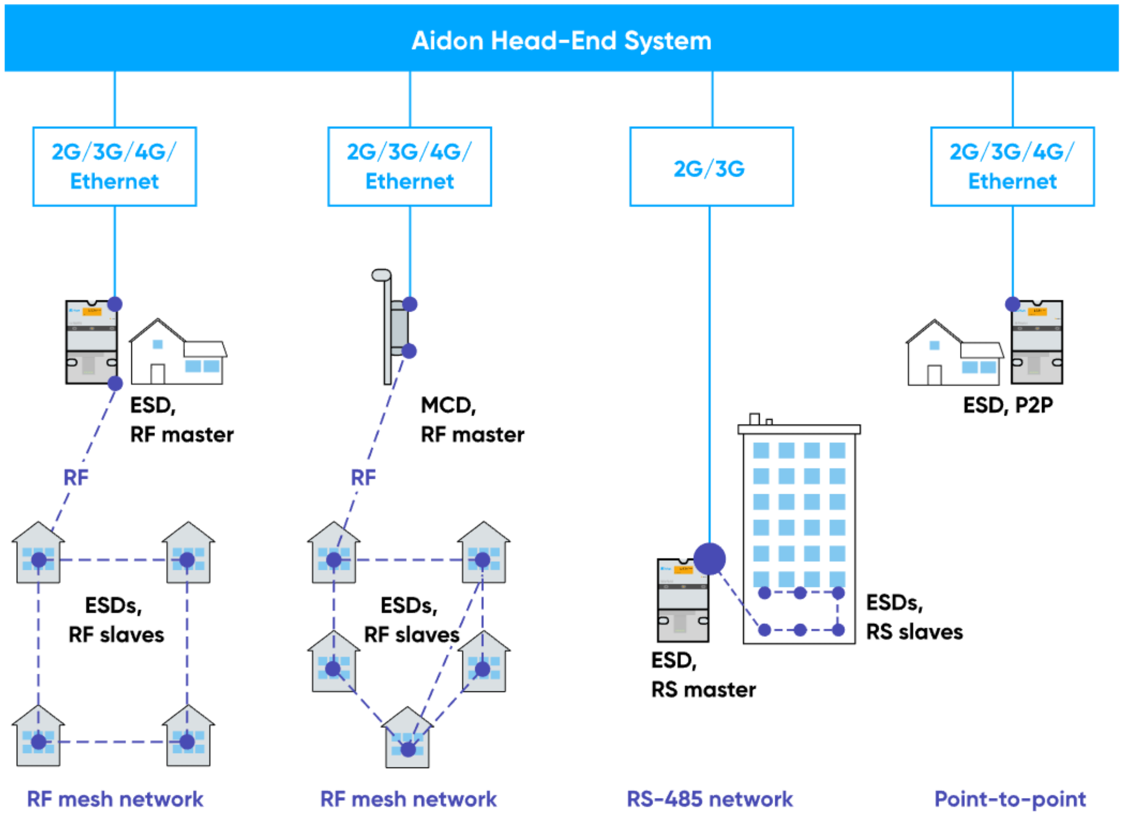


***Figure 17.*** *Aidon ESD communication options [32].*

Aidon has decided to look into new MTC technologies to further improve their communication capabilities. For a new technology to be selected, it needs to meet the requirements of Aidon regarding data rate, coverage, latency, availability, reliability and cost efficiency. According to Aidon, data rate requirement for their network is around 3 kbps with a latency requirement of 20 s. Their RF devices currently have a link budget of 130 dB and they operate in the Scandinavian area.

With the goal of improving their network for optimal communication, Aidon can look to improve the existing wireless mesh network or they can switch technologies altogether. There may be a third possibility of simultaneously having the existing wireless mesh network function with another communication technology. However, since the viability and feasibility of such a solution is exceedingly difficult to evaluate with the available information, it is not considered in this thesis.

# 5. CONCLUSION

In this thesis the most prominent wireless communication technologies for MTC applications were investigated and compared to find an optimal solution for the metering network of Aidon Oy.

As Aidon has decided to optimize their communication network they are left with a choice of either improving on their existing communication solution of wireless mesh technology or switching to another technology altogether. It is currently unclear how much can be done to improve upon the existing wireless mesh solution, which makes recommendations on actions taken difficult. If it is possible to optimize the communication solution already in place for Aidon in a cost-efficient way, continuing the use of wireless mesh networks is a viable option. However, if it is decided that wireless mesh technology is no longer enough to meet the requirements of Aidon, a new technology needs to be selected.

The most prominent wireless communication technologies for MTC purposes at the time of writing are eMTC, NB-IoT and EC-GSM-IoT for licensed technologies and IEEE 802.15.4, Wi-Fi HaLow, Bluetooth Low Energy, wireless mesh, LoRa and Siqfox for unlicensed technologies. Recommendation for a new communication technology for Aidon is steered towards licensed technologies. Licensed technologies have more appeal in terms of reliability and consistency on a global scale due to them being based on extensive global standards. In addition, they operate in the licensed frequency spectrum making them less prone to outside interference. The unlicensed technologies generally are more flexible in terms of device deployment especially in areas with poor coverage, since the licensed technologies are dependent on relatively rigid infrastructure. However, since the network connectivity of licensed technologies and the infrastructure behind it are being developed and maintained by independent operators, new IoT applications can be deployed without the need to install, manage and operate an IoT connectivity solution.

From the licensed MTC technologies presented in this thesis, EC-GSM-IoT has the least appeal. It competes rather well in terms of performance and GSM networks have a global presence. However, it is slowly fading away as it is being overshadowed by newer technologies and their features. GSM spectrums are being refarmed as network operators appear to be turning to other technologies causing the viability of EC-GSM-IoT to decrease as time goes by.

The remaining prominent licensed technologies are eMTC and NB-IoT. NB-IoT is purpose built for low-end IoT applications as it has very low data rates, power consumption and device complexity. Aimed more towards mid-range IoT applications, eMTC has decent data rates, low power consumption and low device complexity. Both NB-IoT and eMTC have a maximum coupling loss of 164 dB and offer power saving features such as PSM and eDRX. Latencies for NB-IoT (guard-band and in-band deployment) and eMTC are around 8.5 s in areas with poor coverage. If standalone deployment is used for NB-IoT, latency in poor coverage areas drops to 5.1 s.

The main difference between these two technologies is data rate. In good conditions NB-IoT can reach peak data rates of 62.5 kbps for UL and 25.5 kbps for DL while eMTC can reach 375 kbps for UL and 300 kbps for DL with half-duplex operation. A considerable difference, but since the data rate requirement for Aidon is around 3 kbps the disparity is ultimately meaningless. However, a problem arises in extreme coverage conditions for both technologies. With a coupling loss of 164 dB, data rates for NB-IoT can drop to 343 bps for UL and 1 kbps for DL with standalone deployment while data rates for eMTC can drop to 167 bps for UL and 800 bps for DL. Data rates for both technologies drop below the required 3 kbps in poor conditions with NB-IoT performing slightly better. This drop in data rate in combination with the rigid infrastructure required for these technologies could cause issues with deploying devices in areas with underdeveloped network infrastructure. In these situations, a different communication option could be used such as ethernet or 2G/3G/4G networks.

NB-IoT and eMTC for the most part both fulfill the requirements of Aidon in terms of data rate, coverage, latency and reliability. A comparable aspect that still remains is cost efficiency. A lack of publicly available concrete data makes direct comparison of costs difficult. However, considering the lower device complexity and data rate of NB-IoT it is reasonable to assume that both module and its operating costs are lower for NB-IoT. In conclusion, as both technologies have sufficient performance for the purposes of Aidon, the technology with better cost-efficiency should be selected. The available information points to NB-IoT being the more cost-efficient technology; however, the specific prices between different market players may vary and should be accounted for before making a wide scale purchase.

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